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THE EFFECT OF TEMPERATURE ON THE STRENGTH
OF WOOD, PLYWOOD AND GLUED JOINTS*

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Summary

This publication covers experimental investigations made at the Division of Forest Products, Council for Scientific and Industrial Research, Melbourne, during the period December, 1940, to January, 1946, to determine the effect of temperature on the strength of wood, plywood and glued joints. The investigations deal with reversible changes in strength, elasticity, and the like which may accompany variations in the temperature of the material.

Results show that all properties investigated are affected by temperature at some moisture content, in many instances to such an extent that serious error is introduced in mechanical testing and in design where this factor is not taken into account. Temperature coefficients may exceed one per cent. of the value at 20° C. per degree centigrade. Relations are given from which the effect of temperature on certain properties of a species can be estimated quantitatively with considerable confidence for a wide range of temperatures and moisture contents.

*This work was completed and presented to the Timber Mechanics Conference, Ottawa, Canada, in September, 1948
C.95/54.

Summary—continued

PART I. *deals with compression, bending, and toughness tests on Sitka spruce and five Australian species at nominal moisture contents of 8, 12, and 20 per cent. in the range -20 to $+60^{\circ}$ C. Compression tests on these species were extended to zero moisture content and near-saturation, in respective ranges of -20 to $+90^{\circ}$ C. and -20 to $+60^{\circ}$ C. In addition, two low density species were included in the compression tests. Two species were also examined in bending at zero moisture content from -20 to $+80^{\circ}$ C.*

PART II. *covers tests made at 15 per cent. nominal moisture content on standard size hoop pine specimens in compression and shear from zero to 40° C. and in bending at 20 and 40° C., also on $2\text{ in.} \times \frac{3}{4}\text{ in.} \times \frac{3}{4}\text{ in.}$ specimens of the same species in compression from -20 to $+60^{\circ}$ C.*

PART III. *describes tests on hoop pine plywood. At nominal moisture contents of 8, 12, and 20 per cent., tensile and crushing strengths were examined from -20 to $+80^{\circ}$ C. Investigation of crushing strength was extended to include zero moisture content. Modulus of elasticity was examined at all the above moisture contents, but only from -20 to $+60^{\circ}$ C.*

PART IV. *discusses tests on casein, phenol-formaldehyde and urea-formaldehyde glued joints at temperatures from -15 to $+60^{\circ}$ C. in the range 8 to 20 per cent. moisture content.*

PART V. *summarizes the more important features of the investigations in general terms and gives results of independent confirmatory tests.*

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Notation

Statistical Significance

L	linear component
Q	quadratic component
C	..	..	cubic component
B	..	..	biquadratic component
*	..	..	significant at the 5 per cent. level of probability
**	..	..	significant at the 1 per cent. level of probability
n.s.	..	..	not significant at the 5 per cent. level of probability

Property Notation

t	..	..	temperature °C.
x	..	..	moisture content (m.c.) per cent.
$C_{x/t}$	..	..	maximum crushing strength (lb./sq. in.) at x per cent. m.c., $t^{\circ}\text{C}$.
$B_{x/t}$	..	..	modulus of rupture (lb./sq. in.) at x per cent. m.c., $t^{\circ}\text{C}$.
$E_{x/t}$	..	..	modulus of elasticity (lb./sq. in.) at x per cent. m.c., $t^{\circ}\text{C}$.
$F_{x/t}$	..	..	fibre stress at the limit of proportionality (lb./sq. in.) at x per cent. m.c., $t^{\circ}\text{C}$.
Δ_x	..	..	modulus of the linear regression coefficient of strength on temperature (lb./sq. in./°C.) at x per cent. m.c.
P_x	..	..	modulus of the linear regression coefficient of strength on temperature (per cent. of strength at x per cent. m.c., 20° C. per °C.) at x per cent. m.c.
c, b, e, f	..	..	suffixes used with Δ_x and P_x to differentiate between temperature coefficients of maximum crushing strength, modulus of rupture, modulus of elasticity, and fibre stress at the limit of proportionality

Introduction

This publication deals with experimental investigations made at the Division of Forest Products, Council for Scientific and Industrial Research, on the reversible changes in mechanical properties of wood, plywood, and glued joints which may accompany change in temperature of the material. It covers wide and practically important ranges of temperature and moisture content.

The first investigations were planned to determine strength-temperature coefficients for Sitka spruce and fifteen species of Australian timbers at 15 per cent. nominal moisture content in the range -10°C. to $+20^{\circ}\text{C.}$ Despite considerable masking of the results in the early tests by moisture effects, it was concluded that compressive strength parallel to the grain, moduli of elasticity and rupture, and fibre stress at limit of proportionality in bending increase appreciably with decrease in temperature.

The growing use of wooden aircraft at that time emphasized the need for information on the effect of temperature, not only at sub-normal temperatures, but also at high temperatures. Here it seemed logical to expect strength reductions with increasing temperature similar in magnitude to the observed increases at low temperatures, so that, if the latter made for safety in aircraft, then the former would introduce an adverse effect not to be overlooked in design. A study of plywood and glued joints then also became desirable.

Consequently, tests were made on solid timber in the range $+20^{\circ}\text{C.}$ to $+60^{\circ}\text{C.}$ and on plywood and glued joints from -10°C. to $+50^{\circ}\text{C.}$, still only at 15 per cent. nominal moisture content. These showed that the strength properties of solid wood may decrease by as much as one per cent. of its strength at normal temperature for each degree centigrade rise; but with increasing temperature, toughness increased for five species, remained constant for one, and decreased for another.

For hoop pine plywood, reductions were observed in maximum crushing strength parallel, perpendicular

and at 45° to the grain of the outer plies and in tensile strength and modulus of elasticity in the 45° direction. The shear strength of glued joints with urea- and phenol-formaldehyde resins decreased slightly with temperature; casein joints strengthened at both high and low temperatures.

Tests on standard size specimens in compression, bending and shear were made at the same nominal moisture content. These confirmed the effects observed for small specimens and showed that the shear strength of solid wood is also reduced by increase in temperature.

The author (Sulzberger¹) published a short account of these preliminary experiments at 15 per cent. moisture content and proposed the adoption of a standard temperature in routine mechanical testing. In 1944 the temperature of the mechanical testing laboratory at the Division of Forest Products, Melbourne, was standardized at approximately 20°C. The investigations were extended to a range of moisture contents, generally from 8 to 20 per cent., but in some instances from oven-dry to saturation. The results were presented to the Timber Mechanics Conference at Ottawa² in 1948, and a standard temperature of 70°F. (21°C.) was adopted.

The present publication deals with the complete range of investigations but does not treat in detail the work at 15 per cent. moisture content, except for standard size wood specimens in compression, bending and shear.

When these investigations were originated no report of similar investigations on plywood or glued joints was available. A few papers on solid wood had been published, but for the most part these were confined to low temperatures or to very high moisture contents. Apart from tests by Greenhill³, the limited data dealing with wood in the hygroscopic range of moisture contents indicated that the strength of wood in this practical condition was not, or was only slightly, dependent on its temperature. Tiemann⁴ included in a United States Forest Service Bulletin observations on a small number of specimens of longleaf pine, spruce and chestnut which showed

that wet wood decreases very considerably in compressive and bending properties when raised to 127° F. (53° C.) and to 212° F. (100° C.). He also found an increase in strength and stiffness in compression at moisture contents above 20 per cent. on cooling these same species to between 0° F. (— 18° C.) and 15° F. (— 9° C.). The effect did not appear in similar tests on air-dry wood. George⁵ compared the strengths of green and of kiln-dried hard maple, black ash, and white pine at temperatures from a little below freezing point to 20° C. Although only a small number of specimens was tested at each condition, a general increase in strength at low temperatures was reported. George concluded that the influence of cold on the strength of wood is not sufficiently great to be taken into consideration in designing structures, and is always toward increased safety. As the tests were made on machines surrounded by air at atmospheric conditions, the results could not be viewed quantitatively, for, as George observed, the specimens during testing rapidly approached the ambient temperature. Greenhill³ realized the need for controlling the temperature during test when, in 1931, he investigated the strength of beech perpendicular to the grain: his testing apparatus was incorporated in a conditioning chamber so that constant specimen temperature and moisture content could be maintained during the tests. He reported decreases in maximum strength, modulus of elasticity, and load at the limit of proportionality as temperature increased from 60° F. (15½° C.) to 180° F. (82° C.) at moisture conditions from green to 5 per cent. moisture content. At 15 per cent. moisture content, decreases in the respective properties at 140° F. (60° C.) were 18, 38 and 40 per cent. of their values at 68° F. (20° C.). Vorreiter⁶ found respective increases of 50 and 100 per cent. in the compressive and bending strengths of water-soaked spruce on freezing at — 15° C. The strength of frozen wood in bending was also investigated in Japan (Miyai and Oshawa)⁷.

Abstracts of investigations by Thunell^{8, 9} on Swedish pine (*P. sylvestris*) were published in the

Empire Forestry Journal⁸ and in Forestry Abstracts⁹. In the former article decreases in ultimate bending strength and modulus of elasticity at 12 per cent. moisture content were reported in the range — 18·5° C. to + 50° C. Although the second article summarizes tests on the relationship between six strength properties, moisture content, density and temperature, the most important results are claimed by the abstract to refer to impact bending tests. Resistance to impact bending was reported as showing constancy in the range 0° C. to 50° C. at 12 per cent. moisture content, some decrease between 0° C. and — 20° C., and a threefold increase at — 60° C. At 25 per cent. moisture content the resistance was halved by lowering the temperature from + 20° C. to — 17° C. Probably the only prior investigations sufficiently extensive to permit any general correlation being formulated between species and effect of temperature on strength were made by Kollmann¹⁰. It was pleasing to find in this publication when it became available in 1945 that, with a different set of species, Kollmann had derived a proportional relation between temperature effect and density for oven-dry wood in compression which was not appreciably different from that derived by the author. The reduction of compressive strength was found to be proportional to increase in temperature for oven-dry wood from — 190° C. to + 160° C., and also for the one species investigated at 12 per cent. moisture content in the range — 190° C. to + 20° C. From oven-dry to saturation the compressive strength of beech at — 42° C. was shown to be greater than at 20° C. Further compression tests, also bending and impact experiments were made, but these were limited to low temperatures, and to a great extent were concerned with saturated material. Nevertheless, it was shown for four species at moisture contents from 7·5 per cent. to 11·2 per cent. moisture content that their moduli of elasticity at — 35° C. were from 2 per cent. to 10 per cent. higher than at 20° C.; for laminated beech at 7·5 per cent. moisture content no significant variation in impact strength occurred in the range — 50° C. to — 6° C.

It is noticeable from the above résumé of the literature that little information was previously available on the effect of temperature in the useful hygroscopic range of moisture contents, particularly at temperatures above normal. This was probably due to the difficulty in maintaining constant moisture content, while bringing specimens to the test temperature, and both constant specimen temperatures and moisture contents during the actual test.

In most of the investigations to be described, the desired constancy of temperature and moisture content was obtained by incorporating the test equipment in a conditioning chamber in which the specimens were both brought to the required temperature and tested. This air-conditioned testing machine (Fig. 1) was otherwise essentially a conventional shot-loaded universal machine of 6,000 lb. capacity. At temperatures between 20° C. and 90° C. air from the chamber was circulated through an external duct containing heating coils and humidifiers. At lower temperatures

(to -20° C.) the duct was sealed off and cooling was effected by U-shaped refrigerator expansion coils around the testing head; these coils were sometimes used for dehumidifying at 20° C. and low moisture contents. Temperatures could be controlled to about $\pm 0.5^\circ$ C. Interchangeable bending and compression equipment used in this machine is shown in Fig. 2.

Large groups of well matched specimens were tested at each temperature and moisture content. Where any preference could be given, the best matching possible was selected for different temperature groups at the one moisture content and next best between moisture contents. For example, solid specimens of wood were end-matched between temperatures and side-matched between moisture contents. To reduce systematic errors, the allocation of matched specimens to the temperature groups at any one moisture content was made at random.

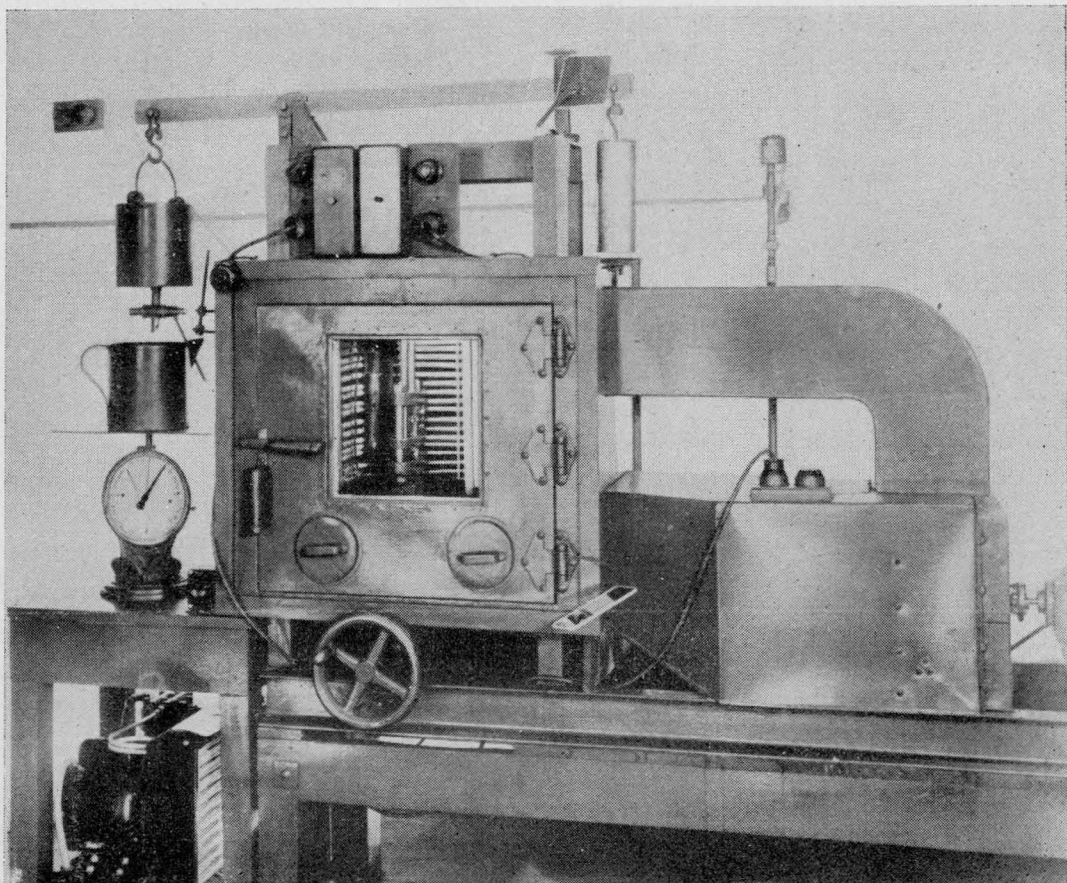


Fig. 1. Air-conditioned testing machine

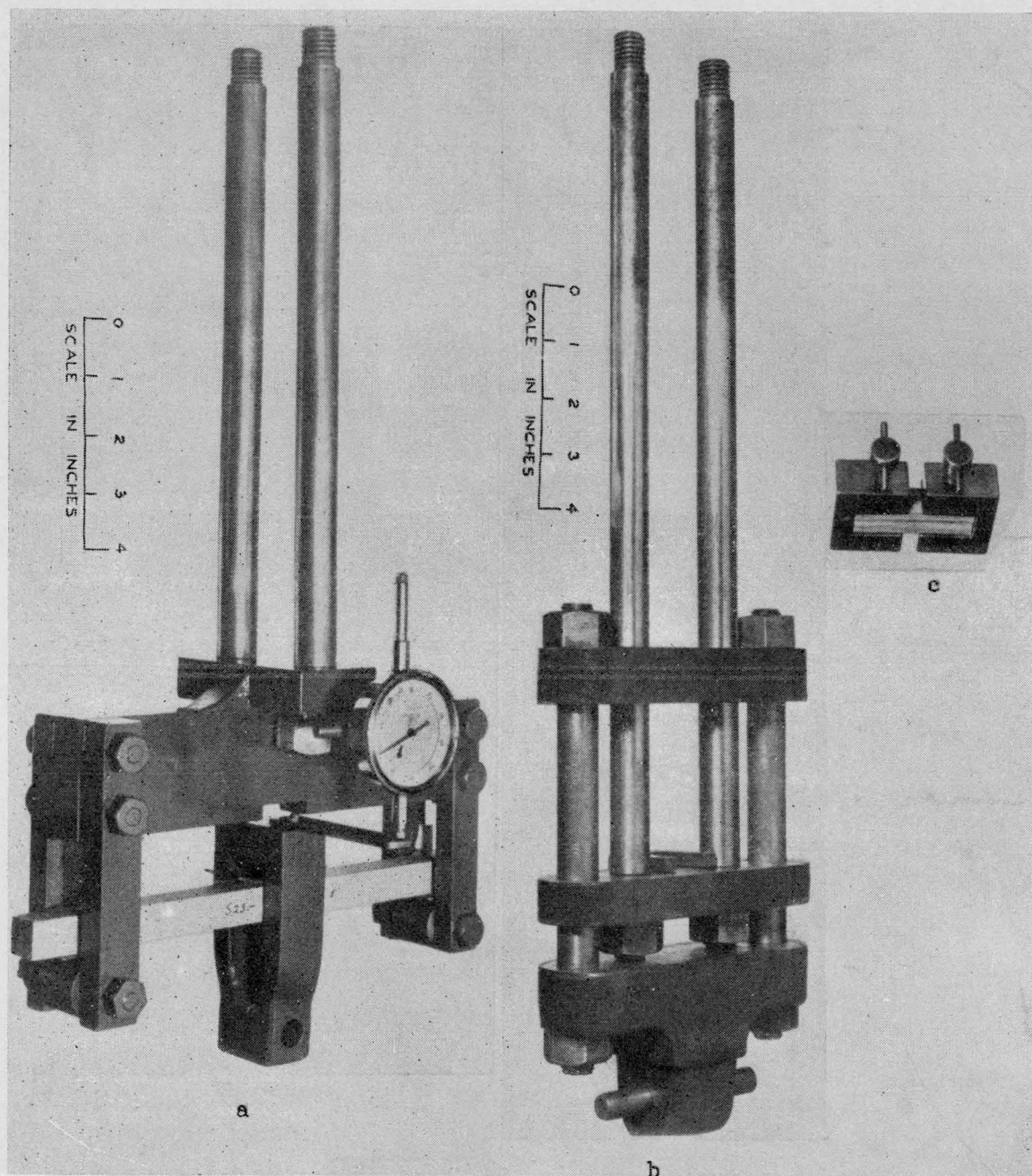


Fig. 2. Interchangeable equipment for special testing machine

- (a) Static bending apparatus;
- (b) Compression apparatus;
- (c) Compression clamp for plywood showing specimen in position

Part I. The Effect of Temperature on the Strength Properties of Solid Wood at Various Moisture Contents

1.0 INTRODUCTION

The effect of temperature on the strength properties of small specimens of solid wood in compression and bending and on standard size toughness specimens was determined for a wide range of moisture contents. Although few species were tested, generalizations are derived from which temperature coefficients for some properties may be estimated with confidence from strength at one temperature.

1.1 SPECIES, PROPERTIES, TEST CONDITIONS AND MATERIAL

Sitka spruce and five Australian species (Table 1) were investigated, the properties and test conditions examined being listed in Table 2. Balsa and the indigenous species kurrajong were also included, in compression tests, on account of their low densities.

Hoop pine, bollywood, coachwood, and silver quandong were represented by one quarter-cut board from each of ten trees. Ten boards of spruce were also used, but these came two from each of five different planks not identified in respect to trees. Mountain ash was also represented by one board

TABLE 1
SPECIES INVESTIGATED

Standard Trade Common Name	Botanical Name
Sitka spruce	<i>Picea sitchensis</i> (Bong.) Carr.
Balsa	<i>Achroma lagopus</i> Sw.
Kurrajong	<i>Sterculia discolor</i> F. v. M.
Hoop pine	<i>Araucaria cunninghamii</i> Ait.
Bollywood	<i>Litsea reticulata</i> Benth.
Coachwood	<i>Ceratopetalum apetalum</i> D. Don
Silver quandong	<i>Elaeocarpus grandis</i> F. v. M.
Mountain ash	<i>Eucalyptus regnans</i> F. v. M.

TABLE 2
PROPERTIES INVESTIGATED AND TEST CONDITIONS

Test	Property	Nominal Moisture Content %	Temperature °C.
Compression ..	Maximum crushing strength parallel to the grain	0 8, 12, 20 .. Saturation ..	— 20, 20, 60, 90 — 20, 0, 20, 40, 60 — 20, 20, 60
Static Bending	Modulus of rupture ; modulus of elasticity ; fibre stress at the limit of proportionality ; deflection to failure	8, 12, 20 ..	— 20, 0, 20, 40, 60
Toughness ..	Radial toughness ; tangential toughness	8, 12, 20 ..	— 20, 0, 20, 40, 60

from each of ten trees, except that at 20 per cent. moisture content approximately half the compression and bending specimens of this species were selected from additional boards from the same logs.

The specimens were prepared in such a way that for every moisture content and species twenty randomly allocated end-matched specimens were available at each temperature for each static test and in each of the two directions for toughness. As already implied, except in the case of mountain ash at 20 per cent. moisture content, the specimens for testing at the various moisture contents were prepared from the same boards and were, in fact, side-matched.

Balsa and kurrajong (investigated only in compression), were tested at -20 , 20 , and 60°C . at nominal moisture contents of 0, 8, 12, and 20 per cent. and near saturation. They were represented each by one billet only, ten specimens being tested at each temperature and moisture content.

In addition, in order to assist in the extrapolation to zero moisture content of data on bending, the moduli of rupture and elasticity of hoop pine and mountain ash were determined for oven-dry material at -20 , 30 , and 80°C . Two side-matched sticks, each containing three end-matched bending specimens, were prepared from ten boards of each species to provide twenty specimens per species at each test condition. The material was not matched with other material of the same species.

1.2 EXPERIMENTAL PROCEDURE

The required equilibrium moisture contents (except in the case of zero moisture content and saturation) were obtained by conditioning the specimens for several weeks in rooms controlled at the appropriate relative humidities. On occasions these rooms suffered some change, resulting in specimens at different temperatures differing appreciably in moisture content. Specimens tested in the oven-dry state were dried at 105°C . to constant weight. Approximate saturation was obtained by soaking the air-dry specimens in water under vacuum for seven days. Bollywood proved difficult to saturate, and before conditioning to -20°C . was subjected to additional impregnation at 200 lb./sq. in. for one hour and at 500 lb./sq. in. for about ten minutes. Even this treatment left it far from saturated and still floating in water.

Compression tests were made in the air-conditioned testing machine. Additional precautions were necessary when testing oven-dry and saturated specimens. The oven-dry specimens were kept in air-tight weighing bottles during conditioning to the test temperature, and consequently were not in contact with moist air except for the few minutes duration of the actual test. Change in the moisture content of the saturated specimens tested at 20°C . was also prevented in this manner. The saturated specimens tested at 60°C . were kept immersed in water at that temperature (in the testing machine conditioning chamber) until immediately before testing. One to two hours were allowed for the specimens to reach the required temperature except in the case of saturated specimens at -20°C ., which, to ensure complete freezing were conditioned at the required temperature for from sixteen to twenty-four hours.

Prisms 2 in. \times $\frac{1}{2}$ in. \times $\frac{1}{2}$ in. were tested in compression, at a constant loading rate of 3,000 lb./sq. in. per min. for all species except balsa and kurrajong for which, on account of their low strengths, the rate was reduced to 1,000 lb./sq. in. per min. For the weakest condition of any species, these rates corresponded to an average loading period of approximately one minute.

Static bending tests (centre-point loading) were made in the air-conditioned machine on 10 in. \times $\frac{5}{8}$ in. \times $\frac{5}{8}$ in. specimens, over an 8 in. span at a constant rate of loading of approximately 70 lb./min., the load being applied to the radial face.

The A.S.T.M. Standard¹¹ radial and tangential toughness specimens (10 in. \times $\frac{5}{8}$ in. \times $\frac{5}{8}$ in.) were tested in a toughness machine (Markwardt and Wilson¹²). As these tests were made outside the conditioning chamber, closely fitting wooden boxes conditioned with the specimens were used to transport the latter to the toughness tester.

1.3 RESULTS AND DISCUSSION

1.31 COMPRESSION PARALLEL TO THE GRAIN

1.311 *General Nature of the Temperature Effect*

The results (except for saturated wood at -20°C .) are presented graphically in Fig. 3 where the observed mean values are plotted after correction to the nominal moisture contents, using factors obtained from the experimental data. At all moisture contents up to saturation, increase in temperature has a considerable weakening effect on maximum crushing strength.

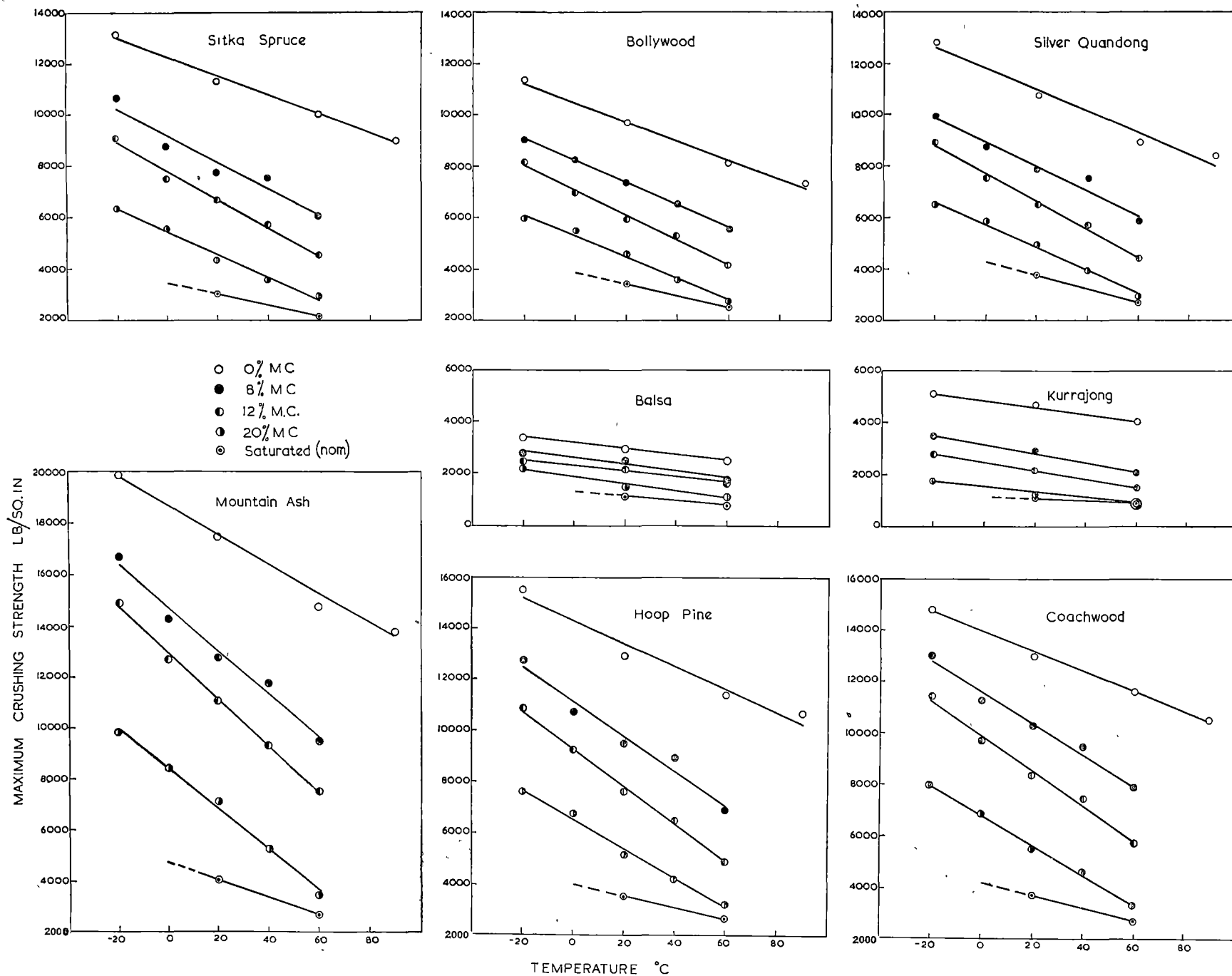


Fig. 3. The effect of temperature on maximum crushing strength of wood in compression parallel to the grain. (2 in. x $\frac{1}{2}$ in. x $\frac{1}{2}$ in. specimens)

In every case from zero to 20 per cent. moisture content, analysis of variance indicates a linear decrease in strength with increase in temperature which is significant at the one per cent. level of probability. At zero moisture content the only deviation (significant at the 5 per cent. level) was recorded for hoop pine; but above this moisture content the non-linear components of the temperature effect were significant at the one per cent. level in nine cases, at the 5 per cent. level in five cases and not significant in ten cases. Nevertheless, as the non-linear components were always small (not exceeding 6.7 per cent. of the total variation between temperatures and generally much less) compared with the linear components, it was concluded that the former could be ignored and that maximum crushing strength parallel to the grain is a linear function of temperature for all species in the ranges zero to 20 per cent. moisture content and -20°C . to $+60^{\circ}\text{C}$. ($+90^{\circ}\text{C}$. at zero moisture content).

Near saturation, the reduction in strength resulting from increasing temperature from $+20^{\circ}\text{C}$. to $+60^{\circ}\text{C}$. was highly significant for all species. At -20°C . a marked increase in strength occurs, presumably due to ice formation (see later). It may be practical to assume linearity up to saturation (above the freezing point), but insufficient temperatures were investigated near saturation to verify this assumption. In the ensuing discussion, reference to a temperature coefficient near saturation will refer to the average reduction in strength per degree centigrade obtained by dividing the difference between strength at 20 and 60°C . by the temperature interval.

The moduli of the calculated linear regression coefficients for the various species and moisture contents are plotted in Fig. 4, temperature effect at the intersection point being assumed equal in magnitude to the effect above freezing point near saturation*. The effect of temperature on maximum crushing strength as measured by these coefficients varies considerably with moisture content and between species. For six species, the effect increases from zero moisture content to between 12 and 14 per cent. moisture content and then decreases, presumably

to a constant value at the intersection point. The maximum values for balsa and kurrajong are not clearly defined, probably as a result of inadequate matching between moisture contents.

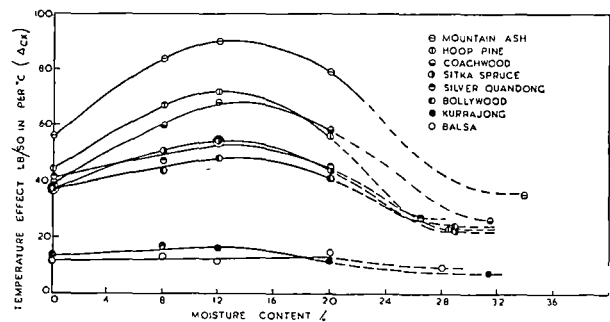


Fig. 4. Variation of temperature effect with moisture content for maximum crushing strength parallel to grain (2 in. \times $\frac{1}{2}$ in. \times $\frac{1}{2}$ in. specimens)

As crushing strength is considered to be a linear function of temperature, if the modulus of the regression coefficient at x per cent. moisture content is Δ_{cx} , the crushing strength C_{x/t_1} at a temperature $t_1^{\circ}\text{C}$. is related to the strength C_{x/t_2} at a temperature $t_2^{\circ}\text{C}$. at the same moisture content by the equation

$$C_{x/t_1} = C_{x/t_2} - \Delta_{cx}(t_1 - t_2) \quad (1)$$

According to the present investigations, this equation is valid at least from zero moisture content to 20 per cent. moisture content in the temperature range -20 to $+60^{\circ}\text{C}$. and to $+90^{\circ}\text{C}$. at zero moisture content. Kollmann¹⁰ showed the relation to hold from -190°C . to $+160^{\circ}\text{C}$. at zero moisture content, and for one species at 12 per cent. moisture content from -190°C . to $+20^{\circ}\text{C}$. Equation (1) is therefore likely to be valid up to 20 per cent. moisture content in at least the range -190°C to $+60^{\circ}\text{C}$.

1.312 Temperature Effect as a Function of Strength

It was observed (Fig. 5) that at each moisture content the effect of temperature on the maximum crushing strength of the various species is reasonably proportional to strength at 20°C . and at the same moisture content†. Thus a confident estimate of temperature coefficients for any species should be

* By drawing strength-moisture content isothermals, constancy of strength at 60°C . above the intersection point may be demonstrated. As constancy at 20°C . is already established, equality of the temperature coefficients at the intersection point and near saturation may reasonably be assumed.

† The strength values at 20°C . used to obtain equations 2A-D are linear regression means; for the intersection point (equation 2E) actual experimental values were used.

possible from these proportional relations, which are as follows:—

$$\Delta_{c0} = 0.0033 C_{0/20} \quad (2A);$$

$$\Delta_{c8} = 0.0062 C_{8/20} \quad (2B);$$

$$\Delta_{c12} = 0.0082 C_{12/20} \quad (2C);$$

$$\Delta_{c20} = 0.0103 C_{20/20} \quad (2D);$$

$$\Delta_{cIP} = 0.0073 C_{IP/20} \quad (2E).$$

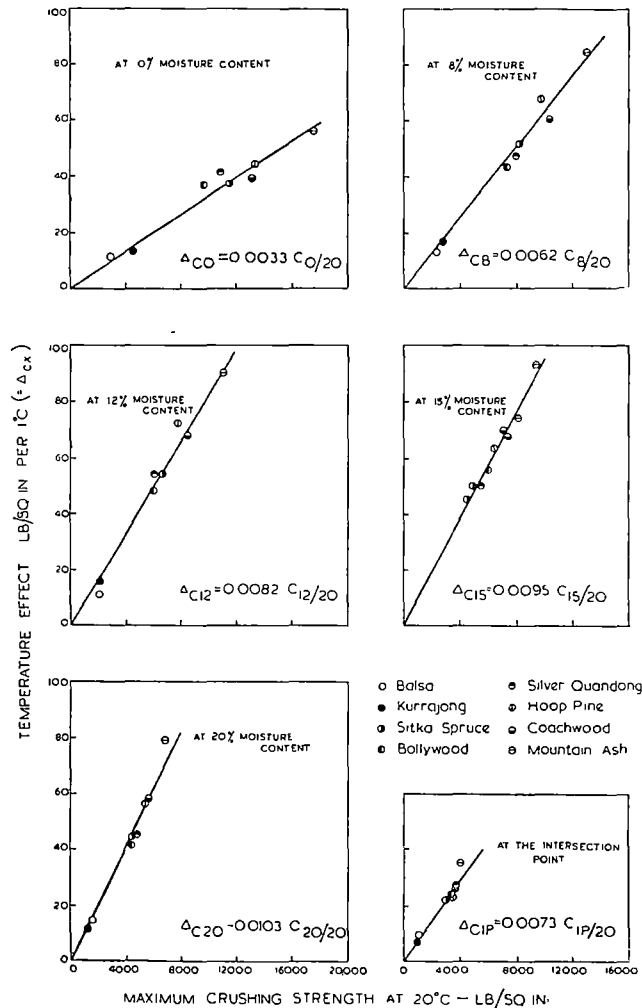


Fig. 5. Temperature effect-strength relations (2 in. x $\frac{1}{2}$ in. x $\frac{1}{2}$ in. prisms) in compression parallel to grain

A similar relation is obtained from the preliminary tests at 15 per cent. moisture content. For tests made in the range 20° C. to 60° C. and in others centred about normal temperature, the corresponding equation for this moisture content is

$$\Delta_{c15} = 0.0095 C_{15/20} \quad (2F)$$

Graphing of the constants of proportionality of these equations (reduced to percentages, Fig. 6) shows that for practical purposes the percentage temperature

effect, defined as

$$P_{cx} = (\Delta_{cx} / C_{x/20}) 10^2 \quad (3)$$

may be considered to increase linearly from 0.33 per cent. per °C. at zero moisture content to 0.97 per cent. per °C. at 16 per cent. moisture content. That is,

$$P_{cx} = 0.33 + 0.04x \quad (4)$$

(in range $0 \leq x \leq 16$)

Beyond 16 per cent. moisture content, the percentage temperature effect increases progressively slowly to a maximum of approximately 1.035 per cent. per °C. near 19 per cent. moisture content, thereafter decreasing towards 0.733 per cent. at the average intersection point.

Within the range of conditions for which strength is proportional to temperature, the values of P_{cx} from the curve (Fig. 6) may be used to calculate directly strength at any given moisture content and temperature from strength at any other temperature and the given moisture content; for elimination of Δ_{cx} from equations (1) and (3) yields the relation

$$C_{x/t_1} = C_{x/t_2} \cdot \frac{100 - P_{cx}(t_1 - 20)}{100 - P_{cx}(t_2 - 20)} \quad (5)$$

Where strength at 20° C. is known or required, equation (5) reduces to

$$C_{x/t} = C_{x/20} [1 - 10^{-2} \cdot P_{cx}(t - 20)] \quad (6)$$

or

$$C_{x/20} = C_{x/t} / [1 - 10^{-2} \cdot P_{cx}(t - 20)] \quad (7)$$

As an example, equation (6) applied to data presented by Kollmann¹⁰ for red beech reduces to

$$C_{0/-42} = 15,645 [1 - 10^{-2} \cdot 0.33(-42 - 20)] \\ = 18,846 \text{ lb./sq. in.}$$

This calculated result is 2.1 per cent. less than Kollmann's experimental value of 19,260 lb./sq. in.

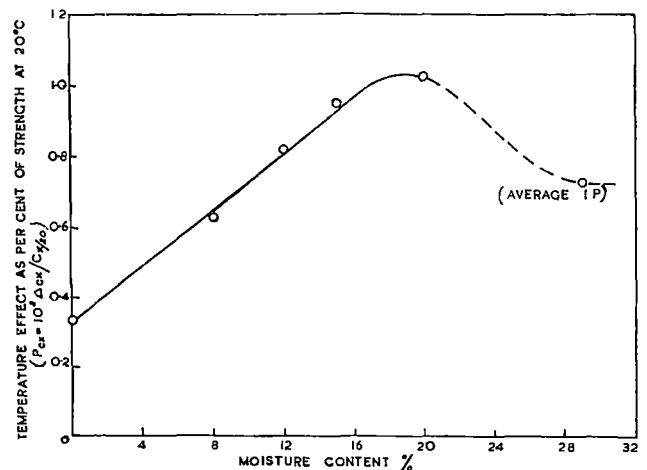


Fig. 6. Temperature effect-strength relations at various moisture contents. (Maximum crushing strength parallel to the grain, 2 in. x $\frac{1}{2}$ in. x $\frac{1}{2}$ in. prisms—average for eight species)

1.313 Crushing Strength of Near-Saturated Wood at -20°C .

It was mentioned previously that near-saturated wood at -20°C . shows a marked increase in strength, presumably due to the presence of ice. In Fig. 7, two curves are shown to illustrate this behaviour and its relation to density at the intersection point. The upper curve drawn through the observation points shows the manner in which the frozen near-saturated wood varies in strength with density. The straight line represents strength at -20°C . at the intersection point, calculated from data at 20°C . and near-saturation on the assumption that the temperature coefficients determined for the range 20°C . to 60°C . apply. The values on this line should be equivalent to strength at -20°C . and saturation, neglecting the effect of ice formation.

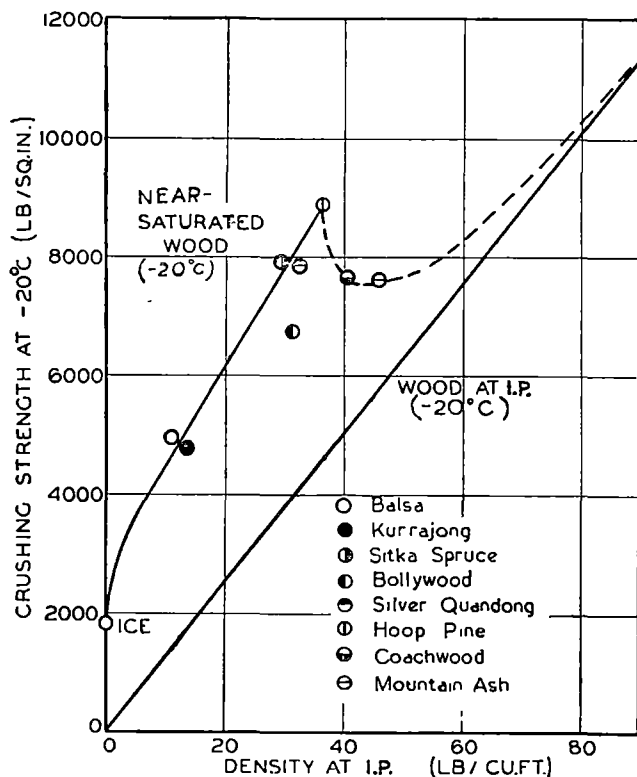


Fig. 7. Crushing strength of wood at I.P. and saturation at -20°C .

On these assumptions, the difference between the ordinates of the two graphs shows the increase in strength due to the presence of ice. The strengthening effect of ice appears to increase with increase in density up to approximately 36.5 lb./cu. ft. (for hoop pine, corresponding to an oven-dry density of 32 lb./cu. ft. as determined on matched specimens)

but beyond this point to decrease abruptly. The probable course of the curve at higher densities is indicated by a broken line which gradually approaches the lower graph, that is the strengthening effect of ice on wood of densities greater than at the transition point diminishes with increase in density. At a point corresponding to wood substance (with an estimated approximate density of 90 lb./cu. ft.) the effect should be zero since this substance contains no free space in which ice might form. On the other hand, at zero density the complete volume would be occupied by ice so that the curve should begin at the crushing strength of ice. Since only widely varying figures for this property, and none at -20°C ., were available, tests were made to determine it experimentally after the manner of the present compression tests. Four specimens gave values very close to 1,800 lb./sq. in. which is much higher than a number of values found in literature but is almost equal to a result quoted by Hutte¹³. Since the ice tested contained considerable air bubbles, it is not unlikely that when formed in wood after impregnation in vacuo it might be even stronger. Extrapolation of the upper curve to zero density indicates an ice strength of 2,800 lb./sq. in. at -20°C . Even this value is insufficient to explain the increase in strength of the near-saturated wood on the basis of the compressive strength of ice without also taking into account its stiffening effect on the wood fibres by filling the voids which otherwise exist between them.

A curve is also given by Kollmann¹⁰ for frozen saturated wood. Although this differs in detail from the present curve, the general form is similar and a theoretical explanation of its shape is given. According to Kollmann, the discontinuity in the curve arises from the melting of ice under pressure. The strength of nominally saturated spruce increased from 3,010 lb./sq. in. at 20°C . to 7,920 lb./sq. in. at -20°C . The gain in compressive strength at -20°C . is 163 per cent., or more than three times the gain reported by Vorreiter⁶ for water-soaked spruce frozen at -15°C .

The extent to which saturation was attained in the present tests was calculated after the manner of Stamm¹⁴. The void volume at test and the additional moisture (per cent. of dry weight) required to bring the specimens to saturation are listed in Table 3.

TABLE 3

VOID VOLUME AND THEORETICAL SATURATION-MOISTURE CONTENT OF SPECIMENS TESTED AT -20°C .
IN A NOMINALLY SATURATED CONDITION

Species	Moisture Content at Test (%)	Void Volume at Test (Fraction of Total Volume)	Difference between Theoretical m.c. at Saturation and m.c. at Test (%)
Balsa	636.4	0.039	29.3
Kurrajong	486.6	0.044	25.1
Bollywood	137.2	0.206	52.5
Spruce	182.9	0.072	20.0
Silver quandong	142.8	0.147	35.9
Hoop pine	148.5	0.034	7.9
Coachwood	131.8	0.033	6.9
Mountain ash	101.6	0.089	16.3

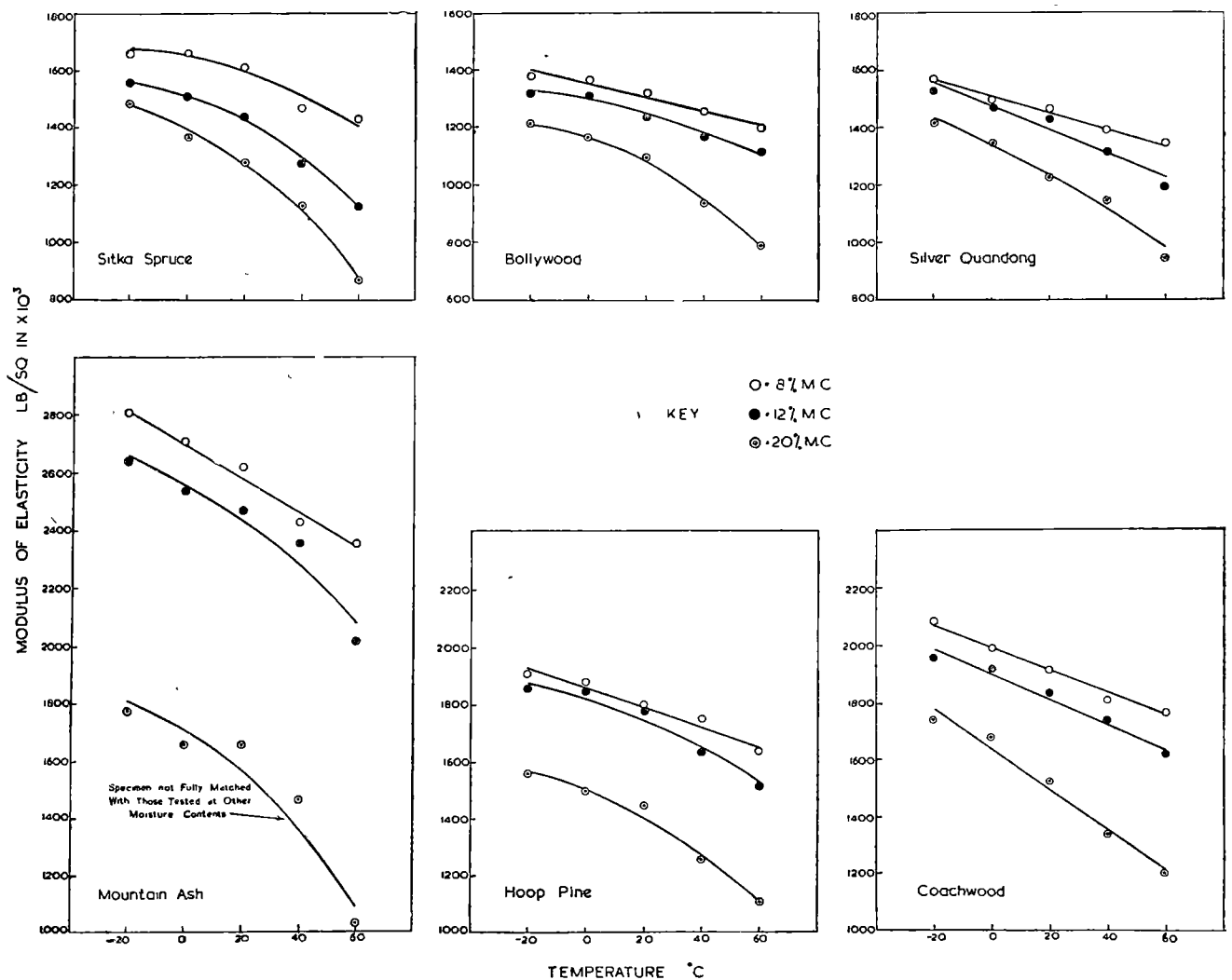


Fig. 8. The effect of temperature at various moisture contents on the modulus of elasticity of wood in bending (10 in. x $\frac{5}{8}$ in. x $\frac{5}{8}$ in. specimens)

1.32 MODULUS OF ELASTICITY IN STATIC BENDING

1.321 *General Nature of the Temperature Effect*

The data (Figs. 8 and 9) obtained from the centre-point static bending tests by application of moisture corrections derived from the experimental results show a general decrease in modulus of elasticity with increase in temperature, the effect increasing with moisture content. The trends of the curves are in accord with the indications of linearity or curvilinearity obtained from statistical examination of the results corrected to the nominal moisture content.

The linear components of the temperature effect, for all species and moisture contents, were significant at the one per cent. level of probability. Neither species (hoop pine or mountain ash) examined at zero moisture content showed significant departure

from linearity at that moisture content or at 8 per cent. moisture content; at 12 and 20 per cent. moisture contents both showed highly significant curvilinearity. Bollywood exhibited trends similar to these species at the three higher moisture contents, while Sitka spruce gave curvilinear relations. Coachwood exhibited no significant deviation from linearity; silver quandong only at 20 per cent. moisture content. It is, therefore, difficult to generalize; but, bearing in mind that the significance of deviations may have been obscured by large errors, visual examination of the plotted observation points (Figs. 8 and 9) might indicate a general trend of the strength-temperature relation from linearity at zero moisture content towards curvilinearity which is slight at 8 per cent. moisture content, but which increases with moisture content.

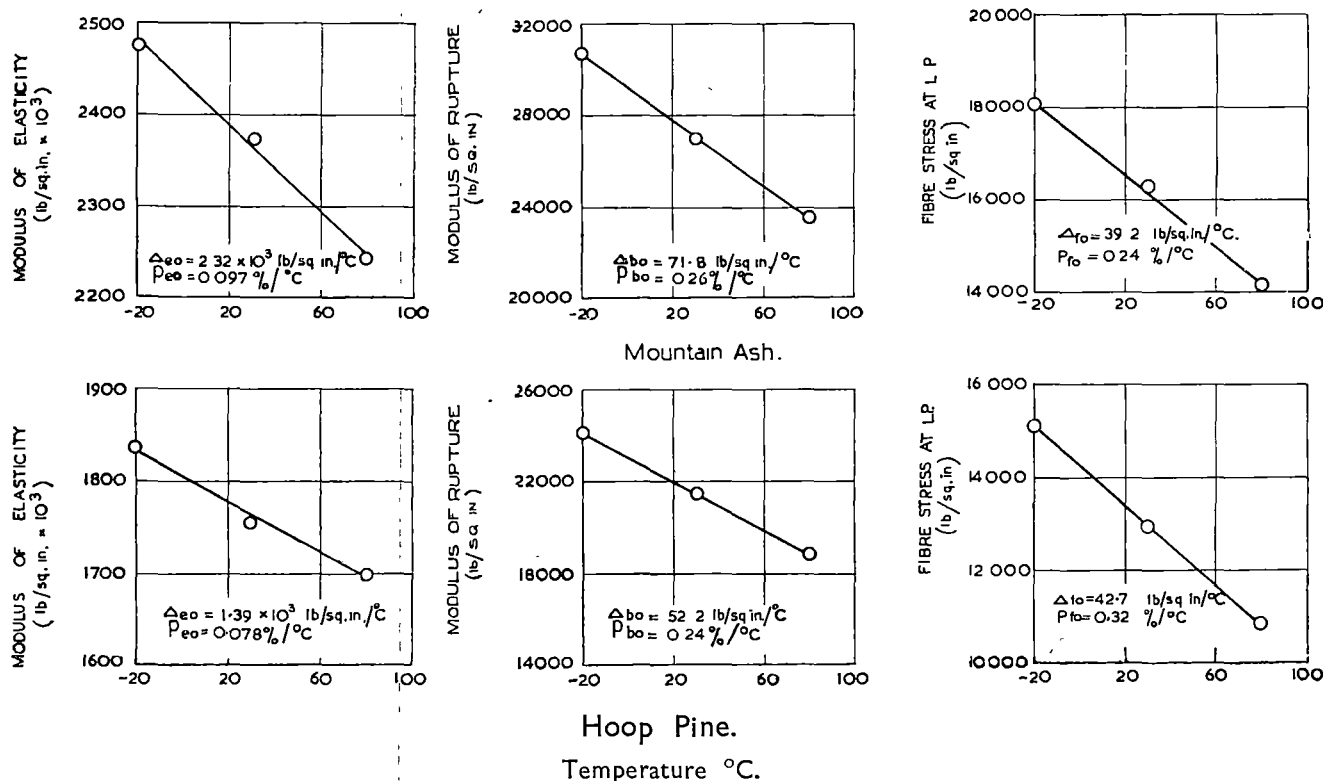


Fig. 9. The effect of temperature on oven-dry wood in static bending. (10 in. $\times \frac{5}{8}$ in. $\times \frac{5}{8}$ in. specimens)

1.322 *Temperature Effect as a Function of Modulus of Elasticity at 20° C.*

The non-linear nature of the effect of temperature on modulus of elasticity observed in some instances makes it undesirable to average the temperature effects for the various species by the use of linear

regression coefficients, as for maximum crushing strength. It is seen (Table 4) that the mean modulus of elasticity of the various species at each test condition are similar, within reasonable limits (spread greatest at high temperatures and moisture contents), when expressed as percentages of strength at 20° C.

TABLE 4

COMPARISON BETWEEN THE MODULI OF ELASTICITY OF SIX SPECIES AT VARIOUS CONDITIONS OF TEMPERATURE AND MOISTURE CONTENT
EXPRESSED AS PERCENTAGE OF STRENGTH AT 20° C. AND THE SAME MOISTURE CONTENT*
(Experimental data corrected to nominal moisture contents)

Species	0 per cent.			8 per cent.					12 per cent.					20 per cent.				
	-20° C.	30° C.	80° C.	-20° C.	0° C.	20° C.	40° C.	60° C.	-20° C.	0° C.	20° C.	40° C.	60° C.	-20° C.	0° C.	20° C.	40° C.	60° C.
Sitka spruce ..	..	..	..	105.9	105.9	102.7	93.8	91.2	112.8	109.2	104.1	92.6	81.7	121.2	111.5	104.2	91.9	70.8
Bollywood ..	..	..	..	105.6	104.8	101.0	96.4	91.8	108.8	108.0	102.2	96.5	84.1	116.4	112.5	105.8	90.4	76.0
Silver quandong ..	..	..	..	107.8	103.0	101.0	95.5	92.7	109.7	106.8	102.5	94.6	86.0	116.5	110.8	100.9	94.3	77.9
Hoop pine ..	104.5	99.4	96.6	106.5	104.8	100.3	97.6	91.4	107.4	106.8	102.8	94.7	87.8	113.4	109.0	105.4	91.6	80.7
Coachwood ..	..	..	..	108.6	103.9	100.2	94.5	92.4	108.0	105.8	101.4	95.9	89.3	116.1	112.1	102.1	89.4	80.0
Mountain ash ..	103.8	99.6	93.7	108.9	105.0	101.6	94.2	91.5	109.8	105.6	102.7	98.1	84.0	117.8	109.9	109.9	97.3	68.2
Average ..	104.2	99.5	95.2	107.2	104.6	101.1	95.3	91.8	109.4	107.0	102.6	95.4	85.5	116.9	110.9	104.7	92.5	75.6

* At zero moisture content strength at 20° C. was taken as the linear regression mean, elsewhere as the grand mean of the experimental means at the five temperatures.

It is, therefore, feasible to use the average of these percentage values at each moisture content and temperature to represent the effect of temperature on modulus of elasticity of wood in general. By plotting the average percentage moduli of elasticity for each moisture content against temperature and adjusting the data from the smoothed curves thus obtained so that modulus of elasticity at 20° C. is equal to 100 per cent., the curves of Fig. 10 (and its transfer graph, Fig. 11) are obtained. It may be significant that these curves, representing an

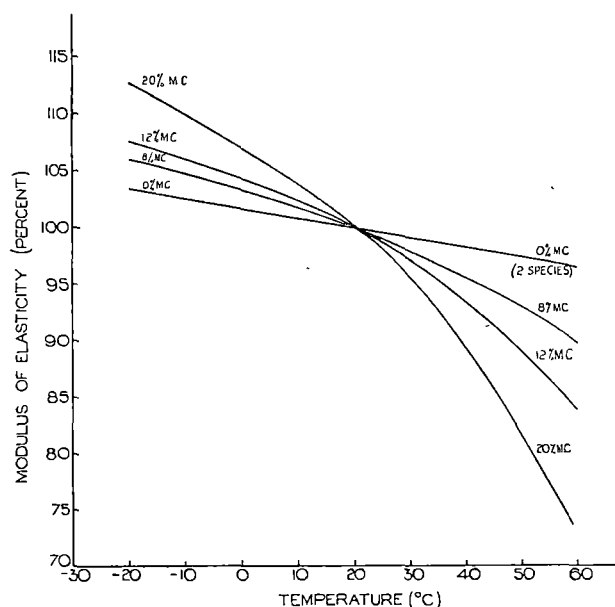


Fig. 10. The effect of temperature on modulus of elasticity in static bending (average of six species)

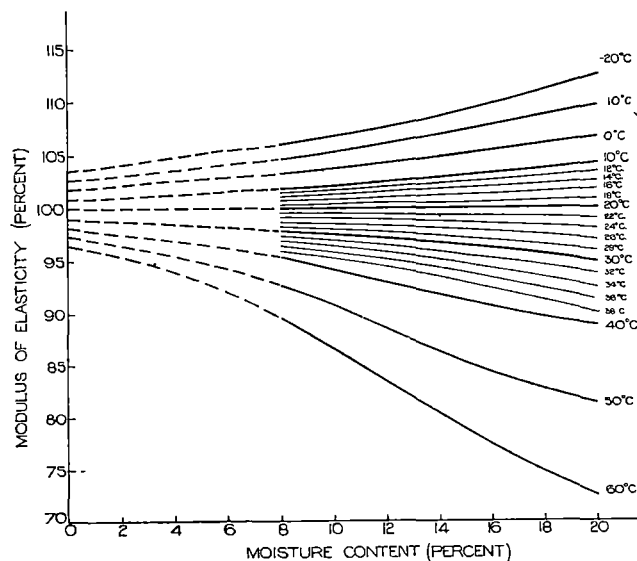


Fig. 11. The effect of temperature and moisture content on modulus of elasticity

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average result for all species, conform to the general trend of temperature effect suggested earlier; namely, linearity of the strength-temperature relation at zero moisture content with slight curvilinearity at 8 per cent. moisture content and increasing curvilinearity at higher moisture contents. The effect of temperature on modulus of elasticity is slight at zero moisture content (average linear regression coefficient for two species equals -0.09 per cent. of value at 20° C. per °C.) but appreciable at the higher moisture contents of the hygroscopic range. For example, at 20 per cent. moisture content, the average modulus of elasticity at 40° C. is 89.1 per cent. of its value at 20° C.

1.33 MODULUS OF RUPTURE IN STATIC BENDING

1.331 *General Nature of the Temperature Effect*

The experimental data corrected to the nominal moisture contents by application of factors derived from the data (Figs. 9 and 12) reveal a considerable reduction in modulus of rupture with increase in temperature for all species and moisture contents examined, the effect varying in magnitude between species and moisture contents. As analysis of the corrected data showed a linear regression of strength on temperature significant at the one per cent. level of probability in all cases and significant deviation only in two instances (at 12 per cent. moisture content, for mountain ash significant at the 1 per cent. level and for silver quandong significant at the 5 per cent. level), it is concluded that modulus of rupture at constant moisture content decreases linearly with increase in temperature. This relation may be written

$$B_{x/t_1} = B_{x/t_2} - \Delta_{bx}(t_1 - t_2) \quad (8)$$

where $B_{x/t}$ is modulus of rupture at x per cent. moisture content and t° C., and Δ_{bx} is the modulus of the regression coefficient of modulus of rupture on temperature. Equation (8) is valid in at least the range -20° C. to $+60^\circ$ C. for moisture contents from oven-dry to 20 per cent. and to $+80^\circ$ C. in the oven-dry condition.

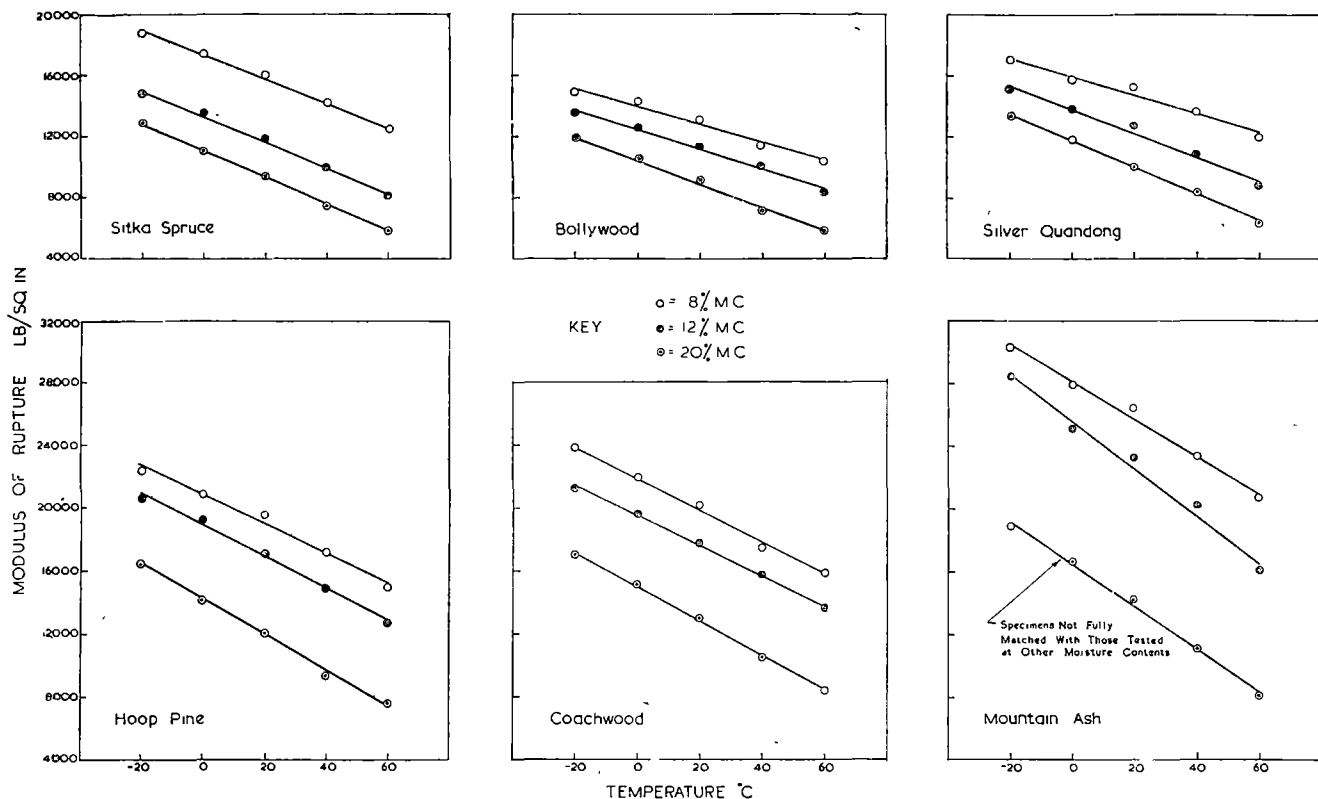


Fig. 12. The effect of temperature at various moisture contents on the modulus of rupture of wood in static bending. (10 in. x $\frac{5}{8}$ in. x $\frac{5}{8}$ in. specimens)

1.332 Temperature Effect as a Function of Strength

It may be shown for modulus of rupture (Fig. 13) that the strength-temperature coefficients, Δ_{bx} , for the various species are reasonably proportional to strength at 20° C., calculation of regression lines through the origin* yielding the following relations:

$$\Delta_{b0} = 0.0025 \cdot B_{0/20} \quad (9A)$$

$$\Delta_{b8} = 0.0047 \cdot B_{8/20} \quad (9B)$$

$$\Delta_{b12} = 0.0062 \cdot B_{12/20} \quad (9C)$$

$$\Delta_{b20} = 0.0092 \cdot B_{20/20} \quad (9D)$$

The average temperature effect increases then from 0.25 per cent. of strength at 20° C. for oven-dry wood to 0.92 per cent. at 20 per cent. moisture content. The percentage temperature effect defined as

$$P_{bx} = (\Delta_{bx}/B_{x/20})10^2 \quad (10)$$

may be estimated from Fig. 14, plotted from equations 9A to 9D. Between 8 and 20 per cent. moisture contents, the percentage temperature effect

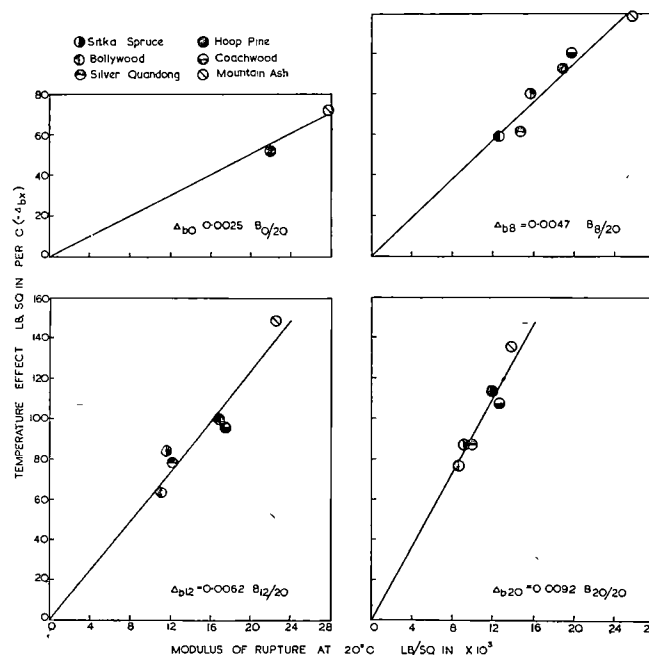


Fig. 13. Temperature effect-strength relations. (10 in. x $\frac{5}{8}$ in. x $\frac{5}{8}$ in. specimens in centre-point bending)

* For both maximum crushing strength and modulus of rupture, passing the regression lines of temperature coefficient on strength through the origin makes no significant change.

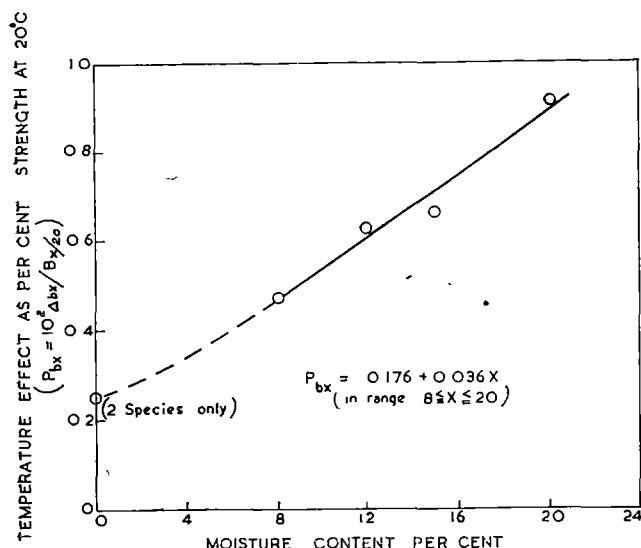


Fig. 14. Temperature effect-strength relations at various moisture contents. (Modulus of rupture in centre-point static bending. 10 in. \times $\frac{5}{8}$ in. \times $\frac{5}{8}$ in. specimens—average for six species)

appears to increase linearly, the equation to the line being

$$P_{bx} = 0.176 + 0.036x \quad (11)$$

(in range $8 \leq x \leq 20$)

The percentage temperature effect at 15 per cent. moisture content calculated in a similar manner for the same six species, from earlier tests in the range 20° C. to 60° C., is 0.66 per cent. at 20° C. This point was included in deriving equation (11).

The following relation, useful in estimating temperature corrections for modulus of rupture, arises from equations (8) and (10):

$$B_{x/t_1} = B_{x/t_2} \cdot \frac{100 - P_{bx}(t_1 - 20)}{100 - P_{bx}(t_2 - 20)} \quad (12)$$

1.34 FIBRE STRESS AT THE LIMIT OF PROPORTIONALITY IN STATIC BENDING

Fibre stress at the limit of proportionality of the six species investigated was found to decrease with increase in temperature at all moisture contents. Despite some ambiguity in the choice of the limit of proportionality from the stress-strain curves and the lack of statistical analyses, the effect seems linear throughout the temperature ranges investigated. The results appear to be adequately represented for oven-dry wood by Fig. 9, and at other moisture contents by the smoothed curves of Fig. 15 which were obtained indirectly by transferring from free-hand isothermals through the observed mean fibre stresses plotted against the mean moisture contents at test. At any given moisture content the moduli

of the linear regression coefficients of strength on temperature ($= \Delta_{fx}$), that is, the slopes of the curves are in general greater for the stronger species, and for practical purposes may be shown to be proportional to strength. It follows that the moduli for the various species, expressed as percentages of strength at 20° C., and the corresponding moisture content ($= P_{fx}$), may be represented by a single average value at any moisture content (Table 5). Plotting of these average proportional temperature coefficients yields the curve of Fig. 16, from which it may be seen that, on a percentage basis, the magnitude of the temperature effect increases from a small value (0.28 per cent. per °C. average for two species) for oven-dry wood to approximately 1.0 per cent. per °C. at 20 per cent. moisture content.

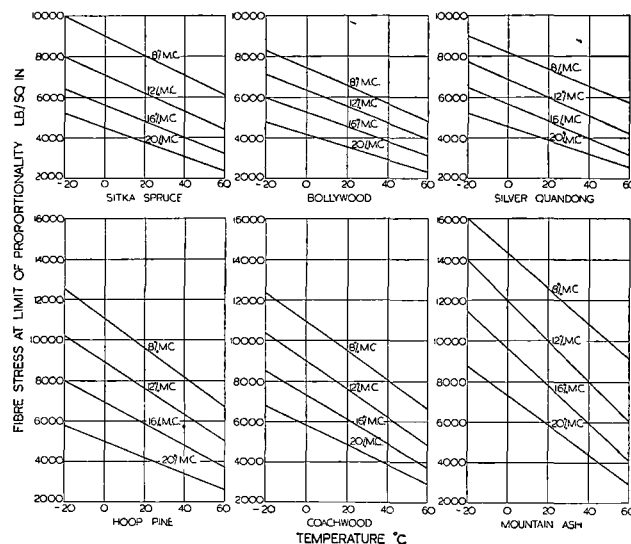


Fig. 15. The effect of temperature on fibre stress at the limit of proportionality of wood in static bending at various moisture contents. (10 in. \times $\frac{5}{8}$ in. \times $\frac{5}{8}$ in. specimens)

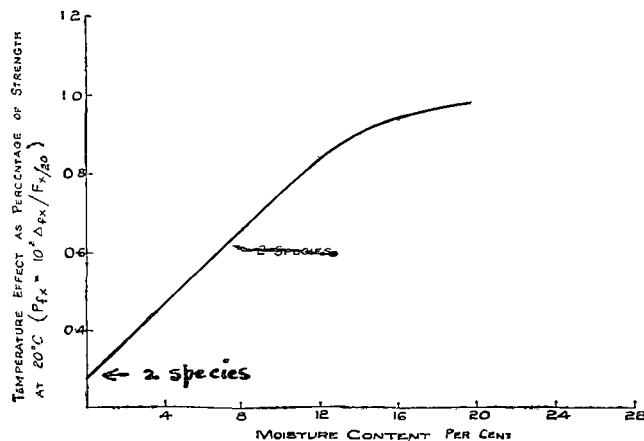


Fig. 16. Temperature effect-strength relations at various moisture contents. (Fibre stress at limit of proportionality in centre-point bending, 10 in. \times $\frac{5}{8}$ in. \times $\frac{5}{8}$ in. specimens—average for six species)

TABLE 5

LINEAR REGRESSION COEFFICIENTS OF FIBRE STRESS AT THE LIMIT OF PROPORTIONALITY ON TEMPERATURE IN STATIC BENDING (10 IN. X $\frac{5}{8}$ IN. X $\frac{5}{8}$ IN. SPECIMENS)

(Experimental data at zero moisture content, data at other moisture contents from smoothed results, Fig. 15)

Species	Moduli of Linear Regression Coefficients of Strength on Temperature at the following Moisture Contents per cent. :—									
	0		8		12		16		20	
	lb./sq. in./1°C.	%/1°C. †	lb./sq. in./1°C.	%/1°C.	lb./sq. in./1°C.	%/1°C.	lb./sq. in./1°C.	%/1°C.	lb./sq. in./1°C.	%/1°C.
Sitka spruce ..	..	..	48.8	0.60	45.0	0.73	40.0	0.83	36.0	0.96
Bollywood ..	..	..	43.8	0.67	39.6	0.71	35.4	0.78	31.2	0.88
Silver quandong ..	..	..	41.2	0.56	48.1	0.81	41.2	0.86	33.1	0.86
Hoop pine ..	42.7*	0.32	73.1	0.76	65.1	0.86	54.8	0.92	40.0	0.95
Coachwood ..	..	..	72.5	0.76	70.0	0.92	61.2	1.00	48.8	1.00
Mountain ash ..	39.2*	0.24	85.6	0.68	100.0	1.00	92.5	1.19	71.0	1.24
Average ..	..	0.28	..	0.66	..	0.84	..	0.93	..	0.98
Maximum ..	..	0.32	..	0.76	..	1.00	..	1.19	..	1.24
Minimum ..	..	0.24	..	0.56	..	0.71	..	0.78	..	0.86

* Specimens not matched with other moisture content groups.

† Values under this heading are moduli of linear regression coefficients of strength on temperature for the given moisture content expressed as percentage of strength at 20° C. and the same moisture content.

1.35 DEFLECTION TO FAILURE IN STATIC BENDING

The data for two species (Table 6) illustrate the general effect of temperature on deflection to

failure. Below 12 per cent. moisture content no great change with temperature is observed, but at higher moisture contents the deformation increases markedly with temperature. The effect varies considerably between species.

TABLE 6

THE EFFECT OF TEMPERATURE ON DEFLECTION AT FAILURE IN STATIC BENDING

Species	Average Deflection (in.) to Failure in Static Bending at the following Nominal Moisture Contents and Temperatures (°C.) :—														
	8 per cent.					12 per cent.					20 per cent.				
	-20	0	20	40	60	-20	0	20	40	60	-20	0	20	40	60
Hoop pine ..	.261	.302	.315	.320	.299	.282	.291	.305	.342	.387	.312	.329	.427	.623	.727
Mountain ash ..	.309	.315	.337	.312	.331	.300	.318	.329	.341	.383	.329	.337	.357	.401	.470

1.36 TOUGHNESS

The mean toughness values at the various test conditions are listed in Table 7. Each value is the mean for twenty specimens except in the cases of silver quandong (sixteen specimens per condition) and bollywood (nineteen radial, seventeen tangential). The specimens omitted were complete end-matched groups so that the means are still comparable between moisture contents and temperatures. Their omission was due to defects, usually severe cross-grain. In cases of abnormal failure which did not merit the exclusion of the whole of an end-matched group, values were fitted by the method of least squares.

Statistically determined, the significance and magnitude of the effect of temperature on toughness at the various nominal moisture contents are listed in Tables 7 and 8 respectively. No correction was made for moisture content; but for the most part the average moisture contents of the temperature groups at any nominal moisture content were little different. It is apparent from these analyses that temperature does in general affect the toughness of wood. The effect is by no means the same for all species or even for different moisture groups of the same species. There is, however, a general trend from decrease in toughness with rising temperature at low moisture contents to an increase with temperature at higher moisture contents. This fact is illustrated by the change from negative linear regression coefficients of toughness on temperature near 8 per cent. moisture content to positive coefficients near 20 per cent. moisture content as shown in Table 8.

In order to gain a better picture of these effects, the results have been graphed (Figs. 17A-L). The toughness-moisture content isothermals were first drawn freehand through the observation points, taking into consideration the results of the statistical analyses, but giving due weight to moisture differences ignored by them. From these graphs the corresponding toughness-temperature curves at 8, 12, 16, and 20 per cent. moisture contents were plotted. The tendency for toughness to decrease with rising temperature at low moisture contents and to increase with temperature at higher moisture contents is obvious from the latter group of graphs; but it is to be noted that at the lower moisture contents the toughness of a number of species does not decrease

throughout the entire temperature range, the decrease in strength with increasing temperature in these cases ceasing at about 20° C. It might then be stated that sub-normal temperatures in general increase toughness at low moisture contents while the main effect of supra-normal temperatures is restricted to an increase in toughness at high moisture contents. At moisture contents below about 14 per cent., supra-normal temperatures have little effect, except on mountain ash. This species is unusual in its behaviour, its toughness showing no increase with temperature except possibly above 18 per cent. moisture content in the radial direction. There is also some doubt as to whether the toughness of bollywood is affected by temperature below 14 per cent. moisture content. In neither direction was significant effect found at this limiting moisture content, nor below it in the radial direction. However, a highly significant temperature effect was found at 8 per cent. moisture content in the tangential direction. As further analysis of the effect into linear and non-linear components showed these to be significant only at the 5 per cent. level, the probable small temperature effect at 8 per cent. was ignored in the graph.

No appreciable reduction in toughness at low temperatures is indicated except near 20 per cent. moisture content. At the latter moisture content the rate of loss of strength tapers off in the case of the two non-pored species investigated, but appears to be constant from + 60° C. to - 20° C. for the pored species. Consequently it is considered probable that much lower temperatures and high moisture contents might combine to produce toughness values considerably below those existing at normal conditions. However, reference to the results for impact strength reported by Thunell⁸ and mentioned earlier, indicates that the behaviour of toughness at very low temperatures cannot be predicted safely from results at other temperatures; for despite the indication of a reduction in the impact strength of Swedish pine at 12 per cent. moisture content in the range 0° C. to - 20° C., there was a threefold increase at - 60° C. At the same time, the reported halving of strength at 20 per cent. moisture content by lowering the temperature from + 20° C. to - 17° C. is in keeping with the observed trend towards greater reduction in strength at low temperatures with increase in moisture content. Although at - 20° C. and 20 per cent. moisture content

TABLE 7
TOUGHNESS DATA AT VARIOUS TEMPERATURES AND MOISTURE CONTENTS†

Species	Temp. at Test (°C).	Radial Toughness (in. lb.) and Moisture Content (%)						Tangential Toughness (in. lb.) and Moisture Content (%)					
		R.T.	M.C.	R.T.	M.C.	R.T.	M.C.	T.T.	M.C.	T.T.	M.C.	T.T.	M.C.
Sitka spruce ..	-20	120.9	7.6	91.6	14.4	95.6	20.4	146.4	7.9	116.0	14.4	116.0	20.6
	0	108.2	7.8	91.6	14.5	102.4	20.5	127.8	7.7	116.6	14.5	135.2	20.3
	20	88.2	8.0	88.2	14.4	101.9	20.0	119.9	7.9	115.8	14.4	138.3	19.9
	40	89.9	7.6	91.8	14.0	113.8	20.2	114.2	7.5	126.2	13.9	153.3	19.6
	60	92.4	7.8	99.6	13.0	118.6	18.3	109.8	7.5	142.0	13.1	167.2	20.1
		(L**Q**)		(L*Q*)		(L**)		(L**Q**)		(L**)		(L**)	
Hoop pine ..	-20	125.3	7.5	100.2	13.7	98.0	20.5	133.5	7.5	104.2	13.6	102.0	20.5
	0	120.8	7.7	103.5	13.8	106.6	20.1	117.0	7.8	100.0	13.8	103.9	20.0
	20	96.6	8.0	87.0	13.9	127.0	19.6	95.5	7.8	97.0	13.8	118.2	19.7
	40	96.8	7.4	87.3	13.2	161.9	20.0	93.8	7.4	93.3	13.5	154.0	19.4
	60	92.4	7.1	99.7	12.8	212.0	19.7	95.9	6.7	105.4	12.8	190.6	18.6
		(L**B*)		(Q**C**)		(L**Q*)		(L**Q**)		(n.s.)		(L**Q*)	
Bollywood ..	-20	79.6	7.7	76.8	13.6	64.3	19.1	76.4	7.8	67.5	13.7	64.5	19.0
	0	79.3	7.7	71.8	13.3	75.1	18.7	83.2	7.7	74.1	13.7	84.2	18.5
	20	70.0	7.8	74.6	13.4	88.7	18.1	65.8	7.7	85.5	13.6	92.0	18.3
	40	71.8	7.3	80.8	13.2	83.8	19.2	67.4	7.3	73.9	13.2	92.8	19.1
	60	70.7	7.6	85.3	13.2	100.1	19.0	69.6	7.4	79.4	13.2	108.5	18.7
		(n.s.)		(n.s.)		(L**)		(L*C*B*)		(n.s.)		(L**)	
Coachwood ..	-20	159.4	7.2	128.1	12.2	126.0	20.8	144.5	7.1	127.2	12.4	115.2	20.9
	0	137.1	7.2	116.6	12.0	132.8	19.1	136.8	7.0	120.1	12.3	114.4	19.5
	20	121.4	7.5	123.6	12.2	139.3	18.4	116.2	7.4	124.0	12.5	118.0	17.8
	40	135.9	7.1	124.1	11.8	141.0	19.5	122.2	7.0	122.6	11.9	126.8	18.8
	60	131.1	7.1	132.6	11.9	140.8	19.2	122.8	6.9	127.0	12.3	126.8	19.9
		(L**Q**)		(Q*)		(L**)		(L**Q**B**)		(n.s.)		(L**)	
Silver quandong	-20	94.9	7.5	77.5	13.7	73.6	19.9	85.4	7.5	80.3	13.7	72.1	19.9
	0	87.0	7.5	75.2	13.8	79.2	19.4	83.5	7.3	72.9	13.8	77.4	19.6
	20	72.4	7.7	78.4	13.7	87.0	19.3	68.6	7.5	75.5	13.6	85.2	19.4
	40	78.6	7.2	77.8	13.1	96.2	19.2	67.8	7.2	71.2	13.2	86.7	19.2
	60	79.8	6.9	83.5	13.4	102.3	19.1	74.5	6.6	77.5	12.6	85.3	18.8
		(L**Q**B*)		(n.s.)		(L**)		(L**Q**C**)		(n.s.)		(L**)	
Mountain ash ..	-20	234.3	7.5	210.5	12.6	185.6	18.2	203.8	7.4	201.4	12.9	185.6	18.2
	0	211.6	7.1	204.5	12.6	183.9	18.3	214.4	7.2	188.5	13.0	183.3	18.2
	20	195.6	7.5	182.4	12.7	173.1	17.7	183.5	7.5	187.8	12.7	171.8	18.2
	40	185.4	7.3	187.9	12.7	175.8	18.0	174.3	7.3	168.7	12.6	167.0	18.1
	60	172.9	7.1	181.1	12.6	190.6	17.2	175.6	6.9	175.6	12.6	167.5	17.7
		(L**)		(L**)		(n.s.)		(L**)		(L**)		(L**)	

† The significance of the temperature effects (determined from analysis of the results before correction for moisture content) are shown in brackets. L: Linear; Q: Quadratic; C: Cubic; B: Biquadratic. * Significant at the 5% level of probability. ** Significant at the 1% level of probability. n.s. Not significant at the 5% level of probability.

TABLE 8

LINEAR REGRESSION COEFFICIENTS OF TOUGHNESS ON TEMPERATURE

Species	Linear regression coefficients of radial and tangential toughness on temperature (in. lb./°C.) at the following nominal moisture contents:—					
	8 per cent.		12 per cent.		20 per cent.	
	Radial	Tangential	Radial	Tangential	Radial	Tangential
Sitka spruce	— 0.38	— 0.43	+ 0.08	+ 0.31	+ 0.29	+ 0.60
Hoop pine	— 0.45	— 0.49	— 0.09	— 0.02	+ 1.42	+ 1.14
Bollywood	— 0.13	— 0.15	+ 0.13	+ 0.12	+ 0.40	+ 0.48
Coachwood	— 0.29	— 0.29	+ 0.08	+ 0.01	+ 0.19	+ 0.18
Silver quandong	— 0.19	— 0.19	+ 0.07	+ 0.04	+ 0.37	+ 0.17
Mountain ash	— 0.74	— 0.48	— 0.38	— 0.36	+ 0.01	— 0.26

some species in the present investigations were 20 to 25 per cent. weaker than at 20° C. and 20 per cent. moisture content, these reduced strengths were not always less than the toughness of the matched specimens at 20° C. and lower moisture contents.

The varying effect of temperature on toughness is unusual in comparison with the consistent decrease in other strength properties with increasing temperature, but an explanation is possible based on specimen strength and deflection to failure. As toughness is a combined function of these two properties, it will tend to be reduced by increasing temperature due to loss of strength; but this reduction will tend to be offset by increased deflection. Deflection to failure during toughness tests was not recorded, but the above explanation agrees with observed deflections in static bending (Table 6). Below 12 per cent. moisture content where deflection to failure does not increase noticeably with temperature, there is little or no increase, and often a decrease in toughness. At higher moisture contents, larger increase in deflection with temperature is accompanied by increase in toughness or, as in the case of mountain ash for which deflection is not so greatly increased, by a reduction in the rate of decrease of toughness.

1.4 CONCLUSIONS TO PART I.

Temperature has a considerable effect on the strength properties of wood in compression, static

bending and toughness but the effect may vary appreciably with moisture content and species.

From oven-dry to 20 per cent. moisture content, maximum crushing strength parallel to the grain, modulus of rupture and fibre stress at the limit of proportionality decrease linearly with rise in temperature. Modulus of elasticity in static bending also decreases with temperature rise. On account of systematic variation between species and moisture contents of the effect of temperature on these properties, it is possible to establish generalizations which are considered applicable to any species.

The strength of wet wood, examined only in compression, is reduced at high temperature; below freezing point it is more than proportionately increased by ice formation.

The effect of temperature on toughness varies widely between species and moisture contents. In some instances, toughness increases with temperature, in others it remains constant, or decreases; but no serious reduction below toughness at some normal condition is indicated for the species and range of conditions (8 to 20 per cent. moisture content, — 20 to + 60° C.) investigated. At the same time, there is a trend towards greater reduction in toughness with decreasing temperature and rising moisture content which, coupled with possible wide variation between species, suggests that each case should be separately investigated.

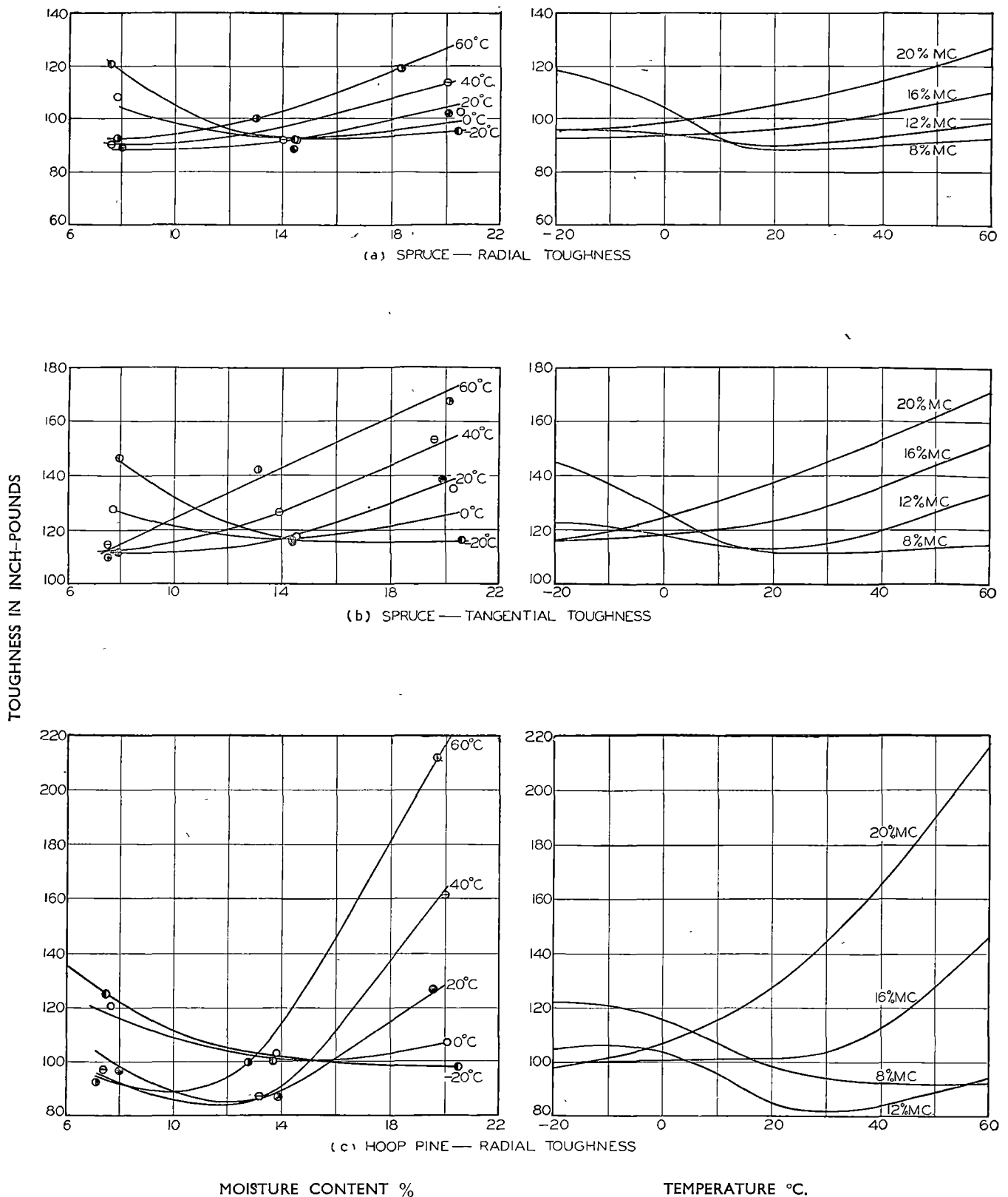
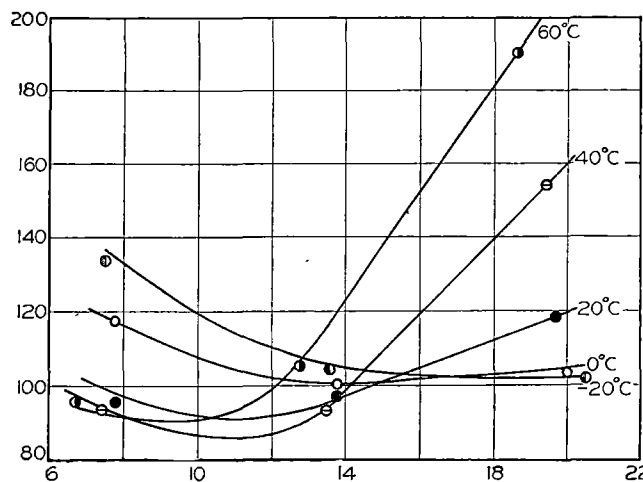
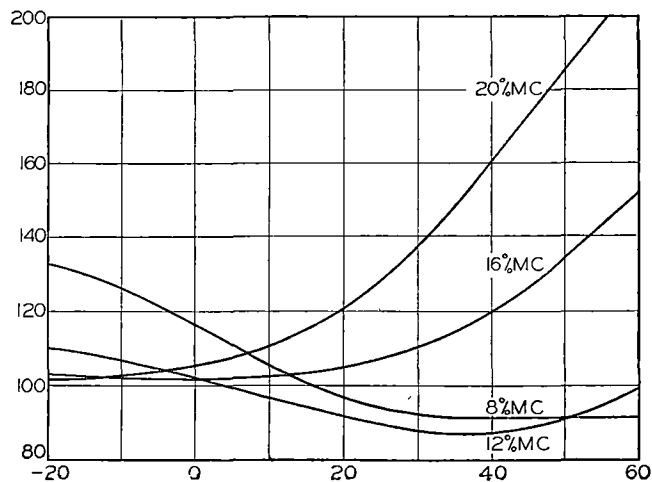


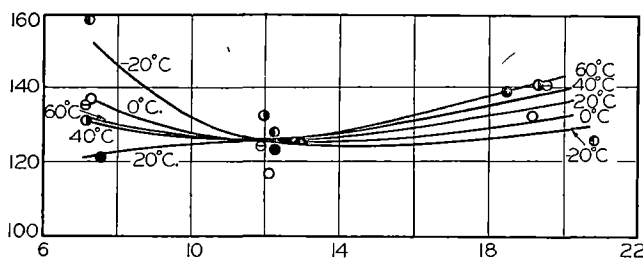
Fig. 17. The effect of moisture content and temperature on toughness



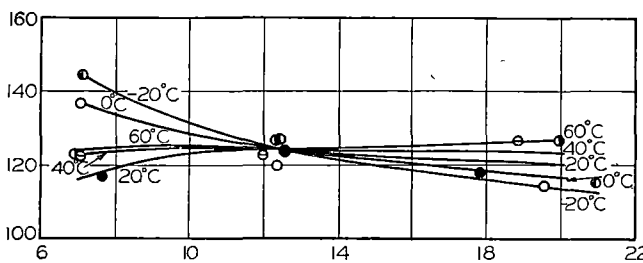
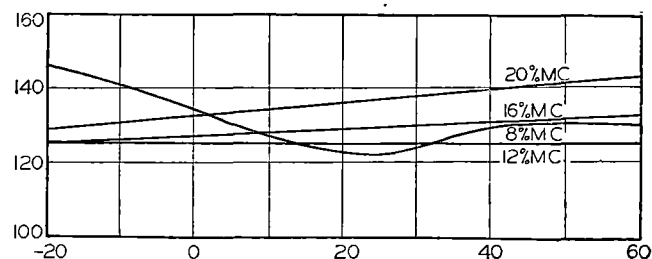
(d) HOOP PINE—TANGENTIAL TOUGHNESS



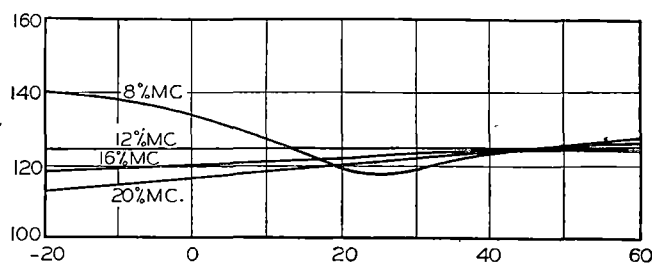
TOUGHNESS IN INCH-POUNDS



(e) COACHWOOD —RADIAL TOUGHNESS



(f) COACHWOOD —TANGENTIAL TOUGHNESS



MOISTURE CONTENT %

TEMPERATURE °C.

Fig. 17—continued. The effect of moisture content and temperature on toughness

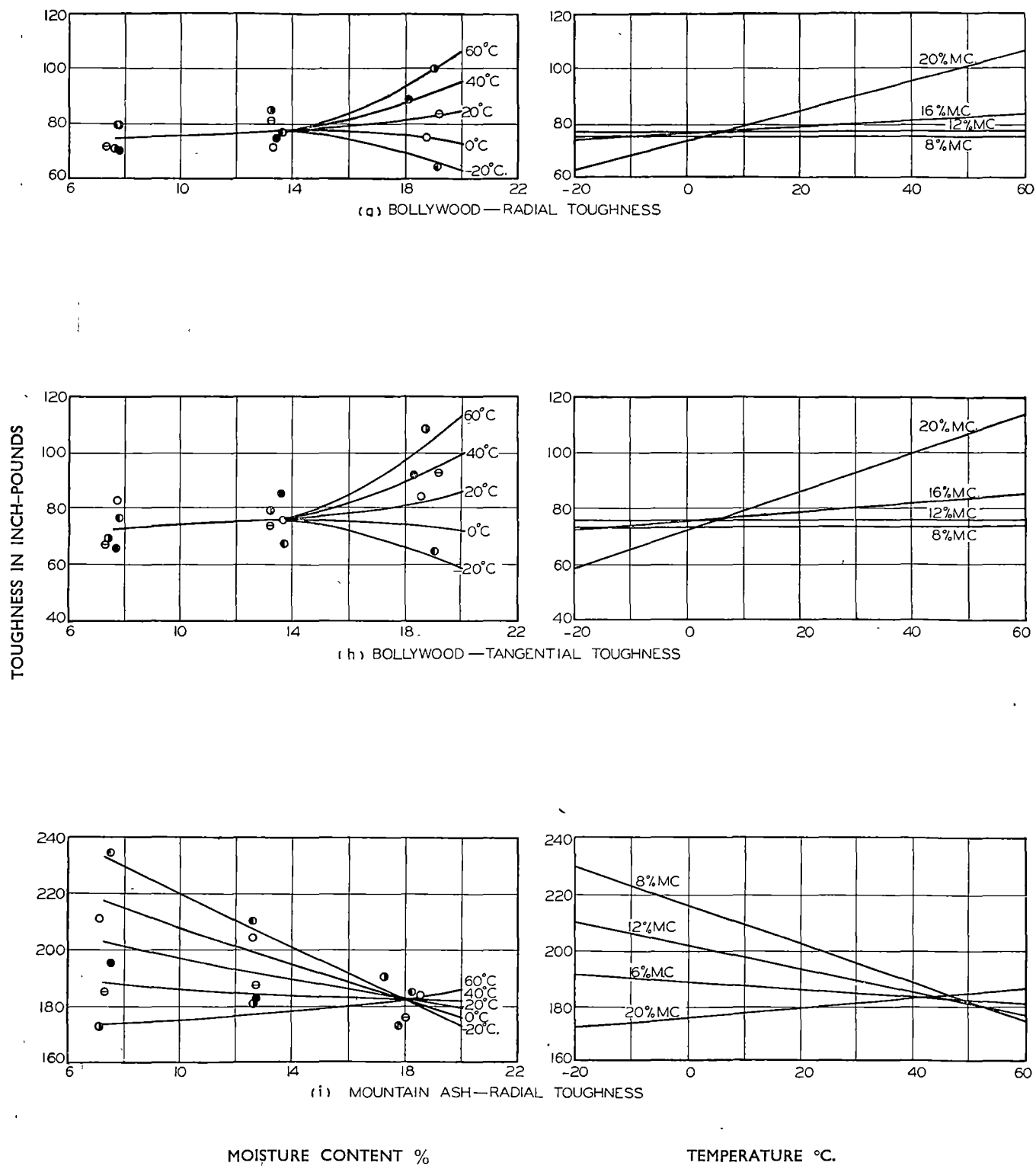


Fig. 17—continued. The effect of moisture content and temperature on toughness

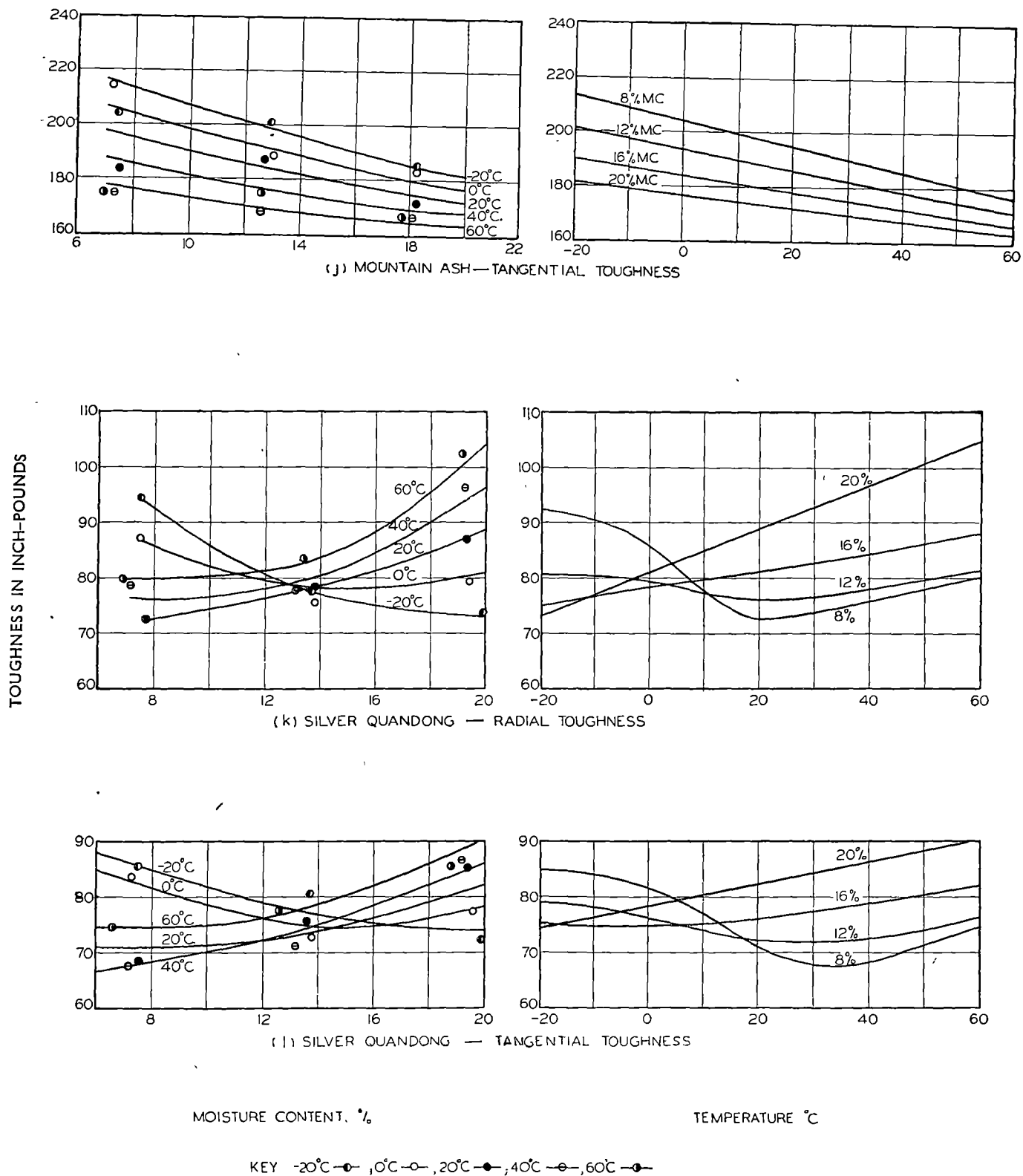


Fig. 17—continued. The effect of moisture content and temperature on toughness

Part II. The Effect of Temperature on Standard Specimens of Hoop Pine in Compression, Bending and Shear at 15 per cent. Moisture Content

2.0 INTRODUCTION

In order to verify the large temperature effects suggested by experiments on small specimens, and to find whether the coefficients obtained are applicable to larger specimens, compression and bending tests were made on solid wood specimens of sizes normally used in timber testing. Standard shear tests were also included as a matter of interest. All tests were generally in accordance with the British and American specifications for testing small clear specimens of timber (Brit. Stand. Inst.¹⁵, Stand. Assoc. Aust.¹⁶, Great Britain, Air Ministry¹⁷, and Amer. Soc. Test Mater.¹¹). As the only available machines of sufficient capacity were not normally air-conditioned, the tests were restricted with respect to temperature and to one species, hoop pine (*Araucaria cunninghamii* Ait.). Carefully controlled check experiments were also made on the largest compression prisms (2 in. x $\frac{3}{4}$ in. x $\frac{3}{4}$ in.) of the same species which could be tested in the air-conditioned machine used in the experiments on small specimens.

2.1 MATERIAL, PROPERTIES AND TEST CONDITIONS

For tests on the standard machines, end-matched specimens (8 in. x 2 in. x 2 in. and 2 in. x 1 in. x 1 in. for compression, 30 in. x 2 in. x 2 in. for bending and 2 in. x 2 in. x 2 in. for shear tests) were prepared as shown in Fig. 18, from one board from each of

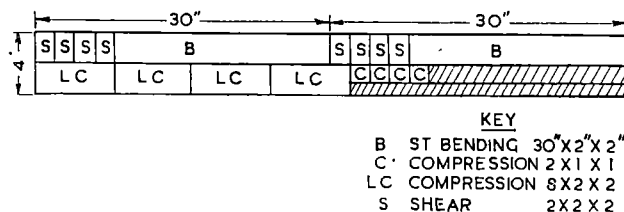


Fig. 18. Preparation of specimens

ten trees. It will be noted that the shear specimens were taken from an end of the bending specimens after the latter had been tested. The end-matched specimens from each board were allocated at random for testing at nominal temperatures of 0, 13.3, 26.7, and 40° C. in compression and shear and at 20 and 40° C. in bending. For compression in the air-conditioned testing machine, two groups of three

end-matched prisms (2 in. x $\frac{3}{4}$ in. x $\frac{3}{4}$ in.) of hoop pine were prepared from each of ten boards, the three specimens in each group being allocated at random for testing at -20, +20, and +60° C. so that twenty well matched specimens were tested at each closely controlled temperature. All specimens were conditioned to approximately 15 per cent. equilibrium moisture content.

2.2 EXPERIMENTAL PROCEDURE

The specimens were brought to the test temperatures in the air-conditioned testing machine cabinet or in a kiln, two hours being allowed for specimens up to 1 in. x 1 in., and upwards of four hours for 2 in. x 2 in. material. Precautions were taken to maintain reasonably constant specimen temperature during transfer to the testing machines and throughout the tests. The testing heads were surrounded by appropriately heated compartments for experiments on bending, shear, and large compression specimens above freezing point. Of the experiments, only shear tests were successfully extended to 0° C., the shear block being insulated from the machine and cooled in ice before each test. All compression specimens were insulated from the testing machines by temperature-conditioned cardboard packing pieces; small specimens tested on a Dennison 30,000 lb. testing machine were surrounded during test by a metal container at the appropriate temperature.

Rates of loading were 6,000 and 3,000 lb./sq. in. per minute respectively for large and small compression prisms, 0.1 in./min. for static bending and 0.015 in./min. for shear specimens.

2.3 RESULTS AND DISCUSSION

All results were corrected to 15 per cent. moisture content before analysis. Corrected results for compression and shear tests are plotted in Figs. 19 and 20.

In compression parallel to the grain, analysis showed the temperature effect on crushing strength to be highly significant with no significant deviation from linearity for either small or large prisms. For both specimen sizes tested on the Dennison testing machine, the linear regression coefficients were similar, -0.69 compared with -0.67 per cent. (of strength at 20° C.) per °C. For check tests on 2 in. x $\frac{3}{4}$ in. x $\frac{3}{4}$ in. specimens in the special testing machine, the regression coefficient was -1.00 per cent. per °C. The larger coefficient obtained from the carefully

controlled check tests leaves little doubt that a similar result should have been obtained at least for the small specimens of approximately similar size (2 in. x 1 in. x 1 in.) tested on a non-conditioned standard machine; possibly also for the large (8 in. x 2 in. x 2 in.) specimens which were tested under equally poor experimental conditions. Comparison with results from 2 in. x $\frac{1}{2}$ in. x $\frac{1}{2}$ in. specimens

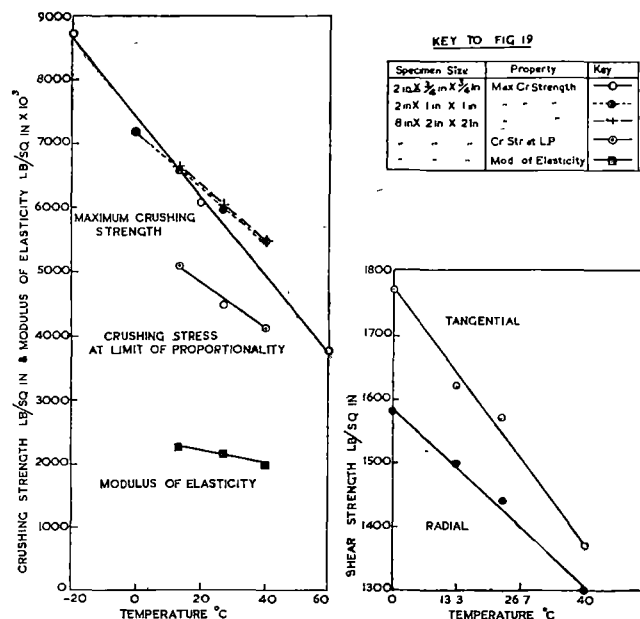


Fig. 19. The effect of temperature on the strength of hoop pine in compression parallel to the grain at 15 per cent. moisture content

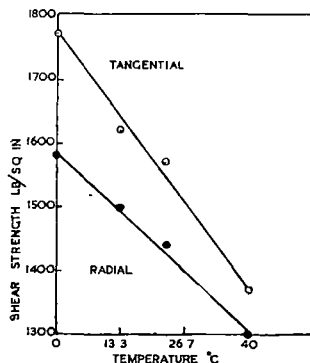


Fig. 20. The effect of temperature on the shear strength of hoop pine at 15 per cent. moisture content.

shows that while the higher coefficient (-1.00 per cent. per $^{\circ}\text{C}.$) is little greater than the coefficients obtained at 15 per cent. moisture content for the same species and the average of six species tested from 20 to $60^{\circ}\text{C}.$ (-0.97 and -0.95 per cent. per $^{\circ}\text{C}.$ respectively) or for the average of eight species (-0.93 per cent. per $^{\circ}\text{C}.$) obtained by interpolation from data at other moisture contents (Fig. 6), the lower coefficients obtained on the Dennison testing machines compare closely only with doubtful results of early experiments at low temperatures. It is, therefore, likely that the effect of temperature on maximum crushing strength parallel to the grain is the same for all usual sizes of specimens.

In compression parallel to the grain (8 in. x 2 in. x 2 in. specimens), crushing strength at limit of proportionality and modulus of elasticity both decrease with rising temperature, the linear effects

being highly significant. The respective regression coefficients obtained are -0.77 and -0.49 per cent. (of value at $20^{\circ}\text{C}.$) per degree Centigrade. No significant deviation from linearity was observed.

In centre point static bending (30 in. x 2 in. x 2 in. specimens, tested over a 28 in. span), modulus of rupture and fibre stress at the limit of proportionality decreased with increase in temperature, the effects being highly significant. Results were obtained only at $20^{\circ}\text{C}.$ and $40^{\circ}\text{C}.$ For this temperature rise, modulus of rupture decreased to 73 per cent. and fibre stress at limit of proportionality to 70 per cent. of their values at $20^{\circ}\text{C}.$ These temperature effects are greater than for 10 in. x $\frac{5}{8}$ in. x $\frac{5}{8}$ in. specimens of the same species, the corresponding reductions for the small specimens being to 86 and 82 per cent. respectively, where the result for fibre stress at limit of proportionality is derived by interpolation from Fig. 15. A decrease of modulus of elasticity to 89 per cent. of its value at $20^{\circ}\text{C}.$ resulted from an increase of temperature to $40^{\circ}\text{C}.$ Although this effect was not significant at the 5 per cent. level of probability, its magnitude is little different from the highly significant reduction (at $40^{\circ}\text{C}.$ to 86 per cent. of its value at $20^{\circ}\text{C}.$) which was observed for modulus of elasticity of small hoop pine specimens; the average reduction in modulus of elasticity observed for the large specimens is identical with the linear regression coefficient obtained for the small specimens in the range 20 to $60^{\circ}\text{C}.$

The results of shear tests, both radial and tangential showed highly significant linear decreases in shear strength with increase in temperature; there was no significant deviation from linearity. The respective regression coefficients were -0.49 and -0.63 per cent. (of strength at $20^{\circ}\text{C}.$) per degree Centigrade.

2.4 CONCLUSIONS TO PART II.

Compression and bending tests on more usual sizes of solid hoop pine specimens at 15 per cent. moisture content show that these are affected by temperature in much the same manner as small specimens; but the magnitudes of the effects may differ.

Appreciably lower temperature coefficients were found for maximum crushing strength of larger specimens tested on the Dennison testing machine, but check experiments suggest that better temperature

control might yield the same higher coefficient (approximately — 1.0 per cent. of strength at 20° C., per degree Centigrade) established for small specimens. Modulus of elasticity appears to be affected much the same for large and small bending specimens, and for (large) compression specimens. It is, therefore, possible that the general relations between maximum crushing strength and temperature, and between modulus of elasticity and temperature, which were derived for small specimens (Part I.) may also apply to other specimen sizes. The relations for modulus of elasticity in bending may also hold for this property in compression.

Modulus of rupture and fibre stress at the limit of proportionality in centre-point static bending are more affected by temperature in large specimens than in small.

Examination of crushing stress at the limit of proportionality in compression parallel to the grain, and of shear strength, confirms the general weakening effect of increasing temperature. Both these properties are linearly affected.

Part III. The Effect of Temperature on the Strength Properties of Hoop Pine Plywood in Compression and Tension at Various Moisture Contents

3.0 INTRODUCTION

By improved matching of specimens, greater attention to moisture control, and extension of the range

of both temperature and moisture content, more extensive and reliable information on the effect of temperature on the compressive and tensile properties of hoop pine three-ply was obtained from the later investigations than from preliminary experiments at 15 per cent. nominal moisture content (Sulzberger¹).

3.1 MATERIAL AND TEST CONDITIONS

The material investigated was $\frac{3}{16}$ -in. hoop pine (*Araucaria cunninghamii* Ait) three-ply bonded with urea-formaldehyde (Beetle cement H, hot hardener No. 12) set at 99° C. to 104° C. at a pressure of 125 lb./sq. in. maintained for 10 minutes.

The properties investigated and the conditions at which tests were made are listed in Table 9.

A total of 180 sheets each 19 in. x 19 in. x $\frac{3}{16}$ in., was prepared from eighteen logs, two from each of nine trees. Sufficient veneers were obtained from a given radius (within ± 0.5 in.) of each log to make nine sheets of plywood. This procedure was duplicated for two logs from one of the trees so that twenty replications of nine matched sheets were obtained.

Tension specimens (Fig. 21) were prepared from these groups in such a way that they were closely matched between moisture contents and grain directions with respect to position in the tree and, for any one grain direction and moisture content, were side-matched (within sheets) between temperatures. At nominal zero moisture content, the same tensile

TABLE 9
PROPERTIES OF PLYWOOD AND THE CONDITIONS OF TEMPERATURE AND MOISTURE CONTENT INVESTIGATED

Property	Direction of Test to Grain of Outer Plies	Nominal Moisture Content (%)	Temperature at Test (°C.)
Tensile Strength ..	Parallel, Perpendicular, and 45°	8, 12, 18 ..	— 20, 0, 20, 40, 60, 80
Modulus of Elasticity in Tension	Parallel, Perpendicular, and 45°	$\left. \begin{array}{l} 0 \\ 8, 12, 18 \end{array} \right\} \dots$	$\left. \begin{array}{l} - 20, 60 \\ - 20, 0, 20, 40, 60 \end{array} \right\}$
Compressive Strength	Parallel and Perpendicular ..	$\left. \begin{array}{l} 0 \\ 8, 12, 18 \\ 22 \end{array} \right\} \dots$	$\left. \begin{array}{l} - 20, 20, 60, 80 \\ - 20, 0, 20, 40, 60, 80 \\ - 20, 20, 60, 80 \end{array} \right\}$
	45°	$\left. \begin{array}{l} 0 \\ 8, 12, 18 \\ 22 \end{array} \right\} \dots$	$\left. \begin{array}{l} - 20, 20 \text{ (duplicated), } 60, 80 \\ - 20, 0, 20, 40, 60, 80 \\ - 20, 40, 80 \end{array} \right\}$

specimens were tested at each temperature, loading being discontinued before failure occurred. As multiple compression specimens (2 in. \times $\frac{1}{2}$ in. \times $\frac{9}{16}$ in.) were used, it was possible to select these from the same sheets in such a way that for each grain direction the specimens were closely side-matched between both temperatures and moisture contents, and between grain directions were matched with respect to position in the tree.

Twenty tension and compression specimens of each grain direction were tested at each listed condition of moisture content and temperature.

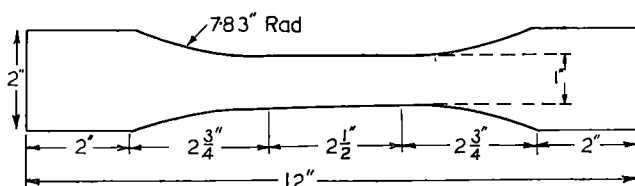


Fig. 21. Plywood tension specimens

3.2 EXPERIMENTAL PROCEDURE

All tests were made using the air-conditioned testing machine.

The required moisture contents except oven-dry and above 20 per cent. were obtained by leaving the specimens in air at controlled humidities and approximate room temperature until equilibrium was attained. Moisture contents greater than 20 per cent. were obtained in a kiln at approximately 40° C. Tension specimens were brought to nominal zero moisture content by drying for approximately 12 hours at 105° C. This drying procedure was also followed for compression specimens tested at 20 and 60° C., but those tested at -20 and +80° C. were dried in vacuo for approximately 18 hours at 60° C. and a duplicated group, tested at 20° C. and at 45° to the grain direction, was dried in vacuo at room temperature, first over calcium chloride, then over phosphorus pentoxide.

All specimens were brought to the required temperature in the test chamber. With the exception of oven-dry tension specimens which were conditioned for only 20 minutes, all were allowed from one to two hours in the chamber before testing. The reduced time for dry tension specimens was sufficient, as shown by thermocouple readings, to bring them very close to the required temperature, at the same time limiting the amount of moisture absorbed. Change in moisture content of compression specimens

near zero moisture content and above 20 per cent. moisture content during conditioning was prevented by the use of air-tight weighing bottles.

A loading rate of 4,000 lb./sq. in./min. conforming to Australian Standard Specification¹⁸ was used for tension parallel and perpendicular to the grain. In the absence of a standard rate for tension in the 45° direction, a loading rate of 2,000 lb./sq. in./min. was adopted in order to make the loading times comparable for all directions, at least at normal temperatures. Stress-strain diagrams were obtained with the aid of a dial type extensometer graduated in 0.0001 in. and having a gauge length of 2 in. Because of possible damage to the extensometer, modulus of elasticity was not investigated at 80° C.

Maximum crushing strength was determined at loading rates of 3,000 lb./sq. in./min. for tests parallel and perpendicular to the grain and 1,000 lb./sq. in./min. for tests at 45° to the grain.

3.3 RESULTS AND DISCUSSION

3.31 TENSILE STRENGTH (PARALLEL, PERPENDICULAR, AND AT 45° TO THE GRAIN)

The effect of temperature on the tensile strength of plywood may be followed from the free-hand curves (Fig. 22) drawn to the experimental points corrected to 8, 12, and 20 per cent. moisture contents, the corrections being derived from a parabola fitted to the observed values at the three test moisture contents.

Temperature has an effect on tensile strength at each moisture content and in each direction. The effect is by no means uniform throughout either the temperature or moisture content ranges; but there is a general trend towards reduced strength at high temperatures and moisture contents which is most seriously manifest in the 45° direction.

While the main effect of temperature on tensile strength parallel to the grain is at high moisture content and temperature, there appears to be a tendency for strength to increase below freezing point, the effect increasing with moisture content. At high temperature there is a marked reduction in strength at 12 per cent. moisture content between 60 and 80° C., and a much greater reduction at 20 per cent. moisture content, between 50 and 80° C. At the most severe test condition (20 per cent. moisture content, 80° C.) the experimental tensile

strength parallel to the grain was 30 per cent. less than at 20° C. and the same moisture content. At 8 per cent. moisture content there is an average strength reduction from -20 to +80° C. of about 0.1 per cent. (of strength at 20° C. per one degree Centigrade).

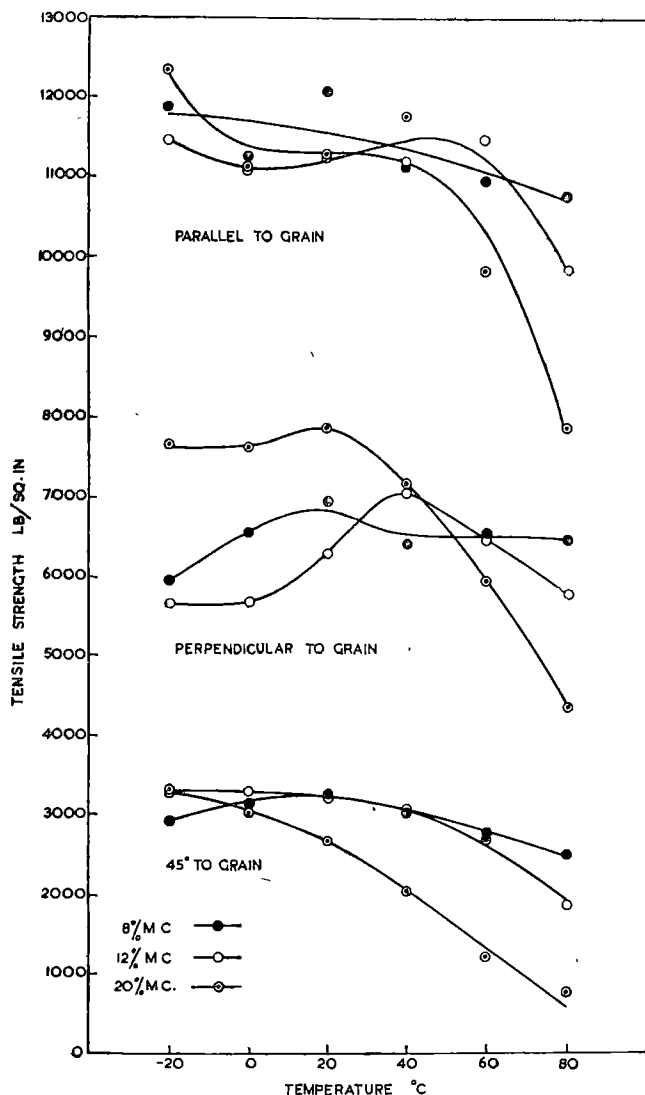


Fig. 22. The effect of temperature on the tensile strength of hoop pine plywood

In the perpendicular direction, tensile strength at 8 per cent. moisture content increased by approximately 14 per cent. between -20 and +20° C., reduced slightly between 20 and 40° C. and remained practically constant between 40 and 80° C. At higher moisture contents strength changed little between -20 and 0° C. but reached maximum values at 40 and 20° C. at 12 and 20 per cent. moisture content respectively. Beyond these

temperatures, strength decreased appreciably, especially at high moisture content. For example, at 20 per cent. moisture content and 80° C. tensile strength perpendicular to the grain was reduced to 56 per cent. of its value at 20° C. and the same moisture content or to 63 per cent. of its value at 20° C., 8 per cent. moisture content.

In general, either increasing temperature or moisture content reduced the tensile strength of plywood at 45° to the grain of the outer plies, but near 8 per cent. moisture content a slight gain in strength between -20 and +20° C. was indicated. The reduction in strength was severe at high temperature and moisture content, at 20 per cent. moisture content, the experimental value at 80° C. being 29.5 per cent. of the corresponding mean at 20° C.

3.32 MODULUS OF ELASTICITY IN TENSION (PARALLEL, PERPENDICULAR AND AT 45° TO THE GRAIN)

The results for modulus of elasticity of plywood in tension were corrected to 8, 12, and 20 per cent. moisture content, using a parabola fitted to the experimental values at the test moisture contents. The corrected data are plotted in Figs. 23 and 24,

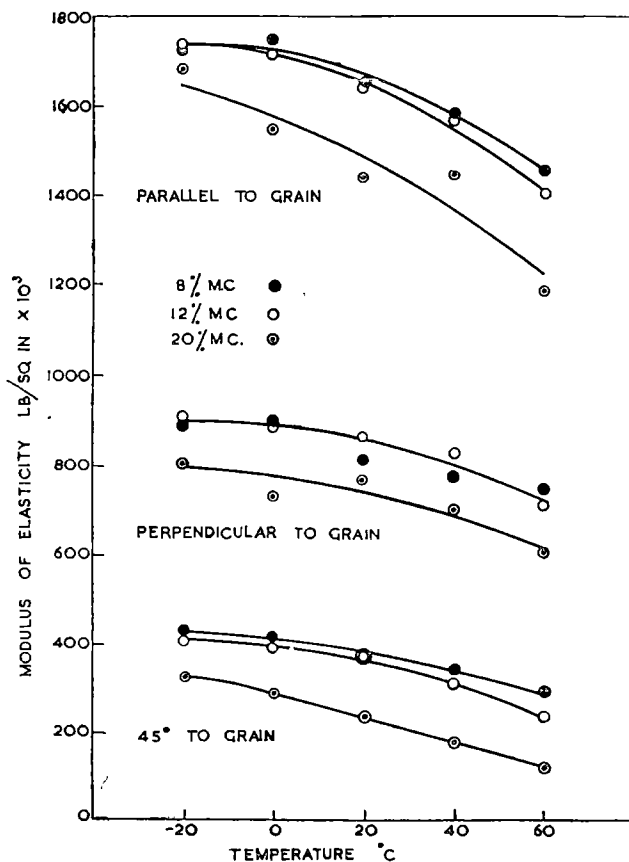


Fig. 23. The effect of temperature on the modulus of elasticity of hoop pine plywood in tension

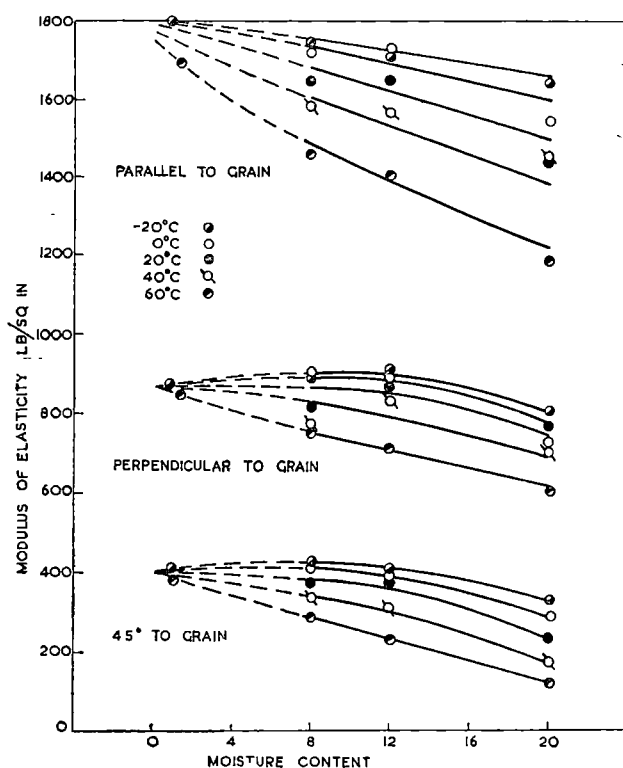


Fig. 24. Variation in temperature effect with moisture content-modulus of elasticity of hoop pine plywood in tension

the latter also containing observations on oven-dry material. The free-hand curves do not correspond exactly between these two figures, smoothing of the individual curves being guided in the second case by other curves in the family and by results near zero moisture content.

The effect of temperature on modulus of elasticity of plywood at zero moisture content is negligible or even non-existent. The experimental means obtained near the oven-dry condition, for the same specimens at each temperature, were all less at 60° C. than at -20° C., but Fig. 24 suggests a residual effect, after correction to zero moisture content, only for the direction parallel to the grain.

There is a definite reduction in modulus of elasticity with increasing temperature at all moisture contents above zero. In the parallel direction, this effect increases noticeably with moisture content throughout the range investigated; but in the perpendicular and 45° directions, any change in the temperature effect between 12 and 20 per cent. moisture contents

is small. However, as modulus of elasticity at 20° C. decreases with increase in moisture content from oven-dry to 20 per cent., the temperature effects expressed as percentages of these values increase throughout the whole range. The two families of curves representing dependence of modulus of elasticity perpendicular and at 45° to the grain on temperature and moisture content (Fig. 24) are almost identical in form and spread; hence, despite a large difference in modulus of elasticity for the two directions, this property is similarly affected in both directions by temperature and by moisture content, and on a percentage basis, the effect of temperature on modulus of elasticity of plywood at 45° to the grain is greater than for the perpendicular direction.

This behaviour in plywood is unusual compared with solid wood for which the temperature effects on modulus of elasticity in bending was found to be proportional to strength. Comparative data (Table 10) confirm the greater proportional effect of temperature for the 45° direction and show modulus of elasticity of plywood in tension parallel and perpendicular to the grain at 8, 12, and 20 per cent. moisture contents to be affected by temperature to much the same extent, on the usual proportional basis, as is the modulus of elasticity of small solid wood specimens of the same species tested in centre-point static bending.

The graphical correlation shown in Fig. 25 illustrates, by the small spread of results about the line $Y = X$, the very marked similarity which exists between the effect of temperature on modulus of elasticity of wood in static bending and of plywood in tension parallel and perpendicular to the grain. For the 45° direction, the equation to the correlation is

$$Y = 2.6X - 160 \quad (12)$$

where X and Y are the respective modulus of elasticity values at a given moisture content and temperature for hoop pine solid wood in static bending and for hoop pine plywood in tension at 45° to the grain, expressed as percentages of the corresponding values at 20° C. and the same moisture content. The spread of results is particularly small.

TABLE 10

COMPARISON BETWEEN THE EFFECTS OF TEMPERATURE ON MODULUS OF ELASTICITY OF HOOP PINE PLYWOOD IN TENSION AND SOLID HOOP PINE IN STATIC BENDING AS PERCENTAGE OF VALUES AT 20° C. AND THE SAME MOISTURE CONTENT*

(Experimental data corrected to nominal moisture content)

Source of Result	8 per cent.					12 per cent.					20 per cent.				
	-20° C.	0° C.	20° C.	40° C.	60° C.	-20° C.	0° C.	20° C.	40° C.	60° C.	-20° C.	0° C.	20° C.	40° C.	60° C.
Hoop Pine Solid Wood in Static Bending (from Table 4—10 in. x $\frac{5}{8}$ in. x $\frac{5}{8}$ in. specimens) ..	106	105	100	98	91	107	107	103	95	88	113	109	105	92	81
Hoop Pine Plywood in Tension Parallel to Grain ..	106	107	101	97	89	108	106	102	97	87	113	106	99	100	82
Hoop Pine Plywood in Tension Perpendicular to Grain ..	108	109	99	94	91	108	106	103	99	84	111	101	106	97	84
Hoop Pine Plywood in Tension at 45° to Grain ..	116	113	101	92	79	119	114	109	89	68	143	126	102	76	52

* Modulus of elasticity at 20° C. taken as the grand mean of the experimental means at the five temperatures.

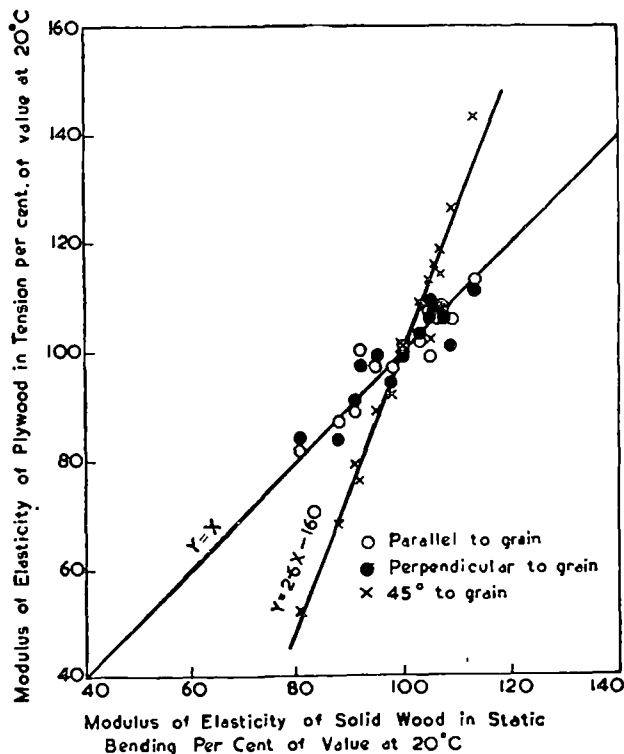


Fig. 25. Comparison between the effect of temperature on modulus of elasticity of hoop pine plywood in tension and hoop pine solid wood (10 in. x $\frac{5}{8}$ in. x $\frac{5}{8}$ in. specimens) in static bending at 8, 12, and 20 per cent. moisture content.

3.33 MAXIMUM CRUSHING STRENGTH (PARALLEL, PERPENDICULAR AND AT 45° TO THE GRAIN)

The effect of temperature and moisture content on the maximum crushing strength of plywood may be followed from Figs. 26 and 27 in which the experimental results are plotted against moisture content for the respective directions of test. The full smoothed curves shown in these graphs connect the observation points at similar temperatures and are, therefore, the crushing strength-moisture content curves appropriate to the temperatures indicated. It may readily be seen that in general strength decreases with increase in either temperature or moisture content. Exceptions occur in the 45° direction below about 12 per cent. moisture content, in which condition the general strength-moisture content relation is reversed, while at zero moisture content for the same direction, temperature appears to have no effect. This reduction in strength in the 45° direction with decrease in moisture content can hardly be attributed to the method of drying since matched groups tested at 20° C., and dried, one at 105° C. and the other over a desiccant at room temperature, gave practically the same result.

The strength-moisture content curves closely fit the observation points and where analyses were made (on uncorrected data), their spacing conforms to the

statistical indication of linear or of non-linear temperature effects. In Fig. 26 the curves are equally spaced to indicate a uniform decrease in strength parallel to the grain with increasing temperature at all moisture contents. In the perpendicular and 45° directions (Fig. 27), the temperature effect is not uniform throughout the complete temperature range, except above approximately 16 per cent. moisture

content. At lower moisture contents the effect is more pronounced at higher temperatures. The effect of temperature at specific moisture contents is shown in Figs. 26 and 27 on transfer graphs prepared from the smoothed strength-temperature isothermals; average reduction in strength with temperature is indicated for two directions by broken lines on the strength-moisture content graphs.

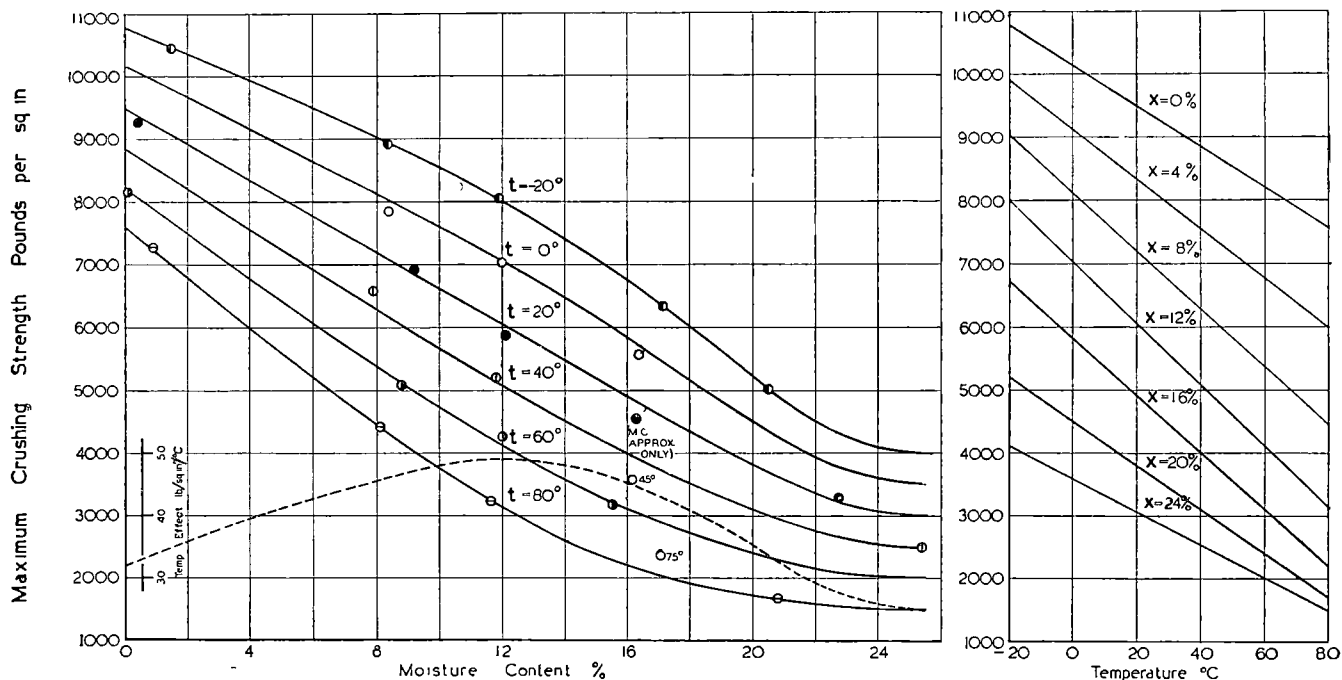


Fig. 26. The effect of moisture and temperature on the crushing strength parallel to the grain of hoop pine plywood

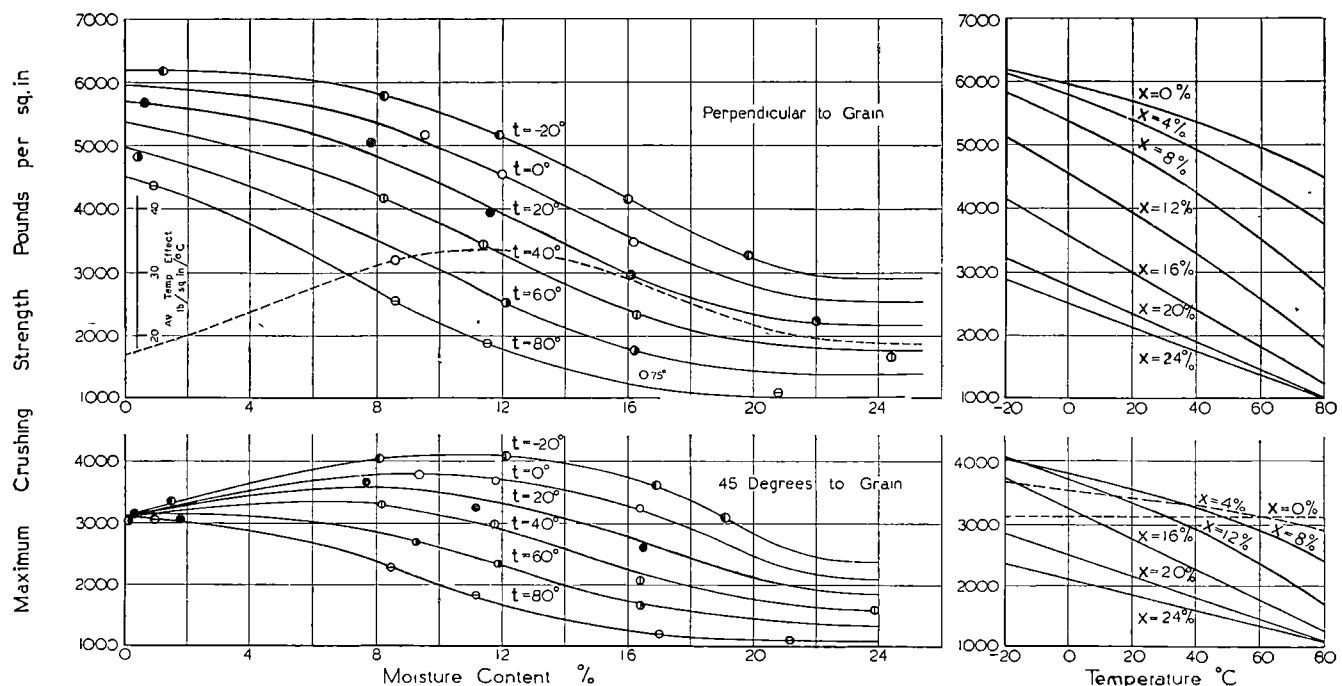


Fig. 27. The effect of moisture and temperature on the crushing strength perpendicular and at 45° to the grain of hoop pine plywood

The effect of temperature on the maximum crushing strength parallel to the grain is compared in Fig. 28 for plywood and solid wood. The proportional temperature coefficients for hoop pine plywood are a little lower than for small solid specimens of the same species, except for coincidence at zero moisture content. From oven-dry to 12 per cent. moisture content, the coefficients for plywood practically coincide with the average results for solid wood; above 12 per cent. moisture content the plywood coefficients are less.

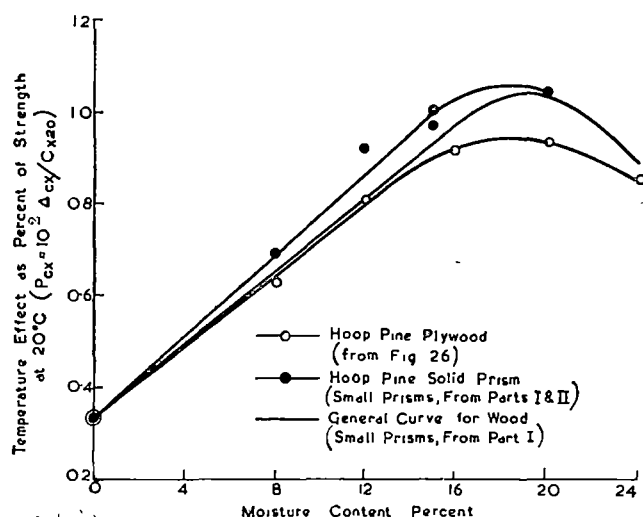


Fig. 28. Comparison of effect of temperature on maximum crushing strength of plywood and solid wood in compression parallel to grain

3.4 CONCLUSIONS TO PART III.

All strength properties of hoop pine plywood investigated are affected by temperature, the most marked trend being towards a serious decrease at high temperature and moisture content. Plywood appears to be particularly temperature sensitive at 45° to the grain.

The manner in which maximum tensile strength parallel and perpendicular to the grain varies with temperature and moisture content is complex; but the interactions are such that only above 60° C. and 12 per cent. moisture content are the strengths reduced much below those encountered at normal temperature and some moisture content in the hygroscopic range. At 80° C., 20 per cent. moisture

content, tensile strength is seriously affected. Although for the parallel direction, tensile strength appears to increase slightly at sub-normal temperatures, for the perpendicular direction it decreases. At 45° to the grain, tensile strength of plywood at 20 per cent. moisture content is seriously weakened by increase in temperature.

On a proportional basis the modulus of elasticity of hoop pine plywood parallel and perpendicular to the grain, between 8 and 20 per cent. moisture content, is affected to the same extent as is the modulus of elasticity of solid hoop pine in static bending. In the 45° direction and for the same moisture content range, the reducing effect of rising temperature is proportionately greater, but also is closely correlated with the effect of temperature on modulus of elasticity of solid wood in bending. Should similar relations exist for other species of plywood, the generalizations (Part I., Figs. 10, 11) developed for determining temperature effect on modulus of elasticity of wood in static bending should apply, between 8 and 20 per cent. moisture content, directly to modulus of elasticity of plywood parallel and perpendicular to the grain; and indirectly to the 45° direction through a correlation for a number of species between percentage modulus of elasticity values for plywood in tension and for solid wood in bending.

Maximum crushing strength of plywood parallel to the grain decreases linearly with increase in temperature at all conditions examined. The observed temperature coefficients expressed as percentages of strength at 20° C. were not very different from those of solid wood of the same species; at zero moisture content they were equal, at other moisture contents the coefficients for plywood were lower. Maximum crushing strength in the perpendicular and 45° directions is affected linearly by temperature above approximately 16 per cent. moisture content; below it there appears to be a departure from linearity, and at zero moisture content temperature has no effect on maximum crushing strength at 45° to the grain.

Part IV. The Effect of Temperature on the Shear Strength of Glued Joints at Various Moisture Contents

4.0 INTRODUCTION

In preliminary investigations on shear strength of glued joints at 15 per cent. nominal moisture content, no seriously detrimental temperature effect was observed. The strength of casein joints increased at both high and low temperatures, while urea- and phenol-formaldehyde joints decreased only slightly throughout the range (-10 to $+50^{\circ}\text{C}.$) investigated. Nevertheless, in view of the range of conditions encountered in practice, the investigations to be described were undertaken on the same adhesives to cover moisture contents from 8 to 20 per cent. over as wide a temperature range as was possible at that time.

4.1 ADHESIVES, MATERIAL, AND TEST CONDITIONS

Hoop pine specimens 8 in. x 1 in. x $\frac{1}{2}$ in. with central glue-lines were used, the specimens being notched to leave an effective glue surface of one inch square (Fig. 29). The usual solid wood was replaced by $\frac{1}{4}$ -in. three-ply, bonded with phenol-formaldehyde (tego film), set at 138° – $149^{\circ}\text{C}.$ at 125 lb./sq. in. for 12 minutes.

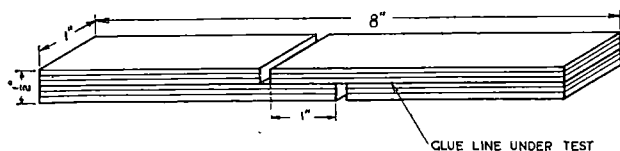


Fig. 29. Glue joint test specimen

Three 20-in. square sheets of the $\frac{1}{4}$ -in. plywood were made from veneers from the same radius (in any one tree) from each of eleven trees. One sheet from each tree was allotted for the preparation of glued joints of each type of adhesive, namely casein, urea-formaldehyde, and phenol-formaldehyde. In effect, three well matched groups of eleven sheets were available, one for use with each glue.

These sheets were sawn centrally along the grain, the halves folded together and bonded with the

adhesives under test to form boards approximately 20 in. long x 10 in. wide x $\frac{1}{2}$ in. thick. As illustrated in Fig. 30, fifteen specimens 8 in. x 1 in. x $\frac{1}{2}$ in. were prepared from each board. The groups of specimens 1 to 5, 6 to 10, and 11 to 15 were then allocated at random for testing at 8, 12, and 20 per cent. nominal moisture contents. The five specimens within these groups were further allocated at random for testing at -15 , 5, 20, 40, and $60^{\circ}\text{C}.$

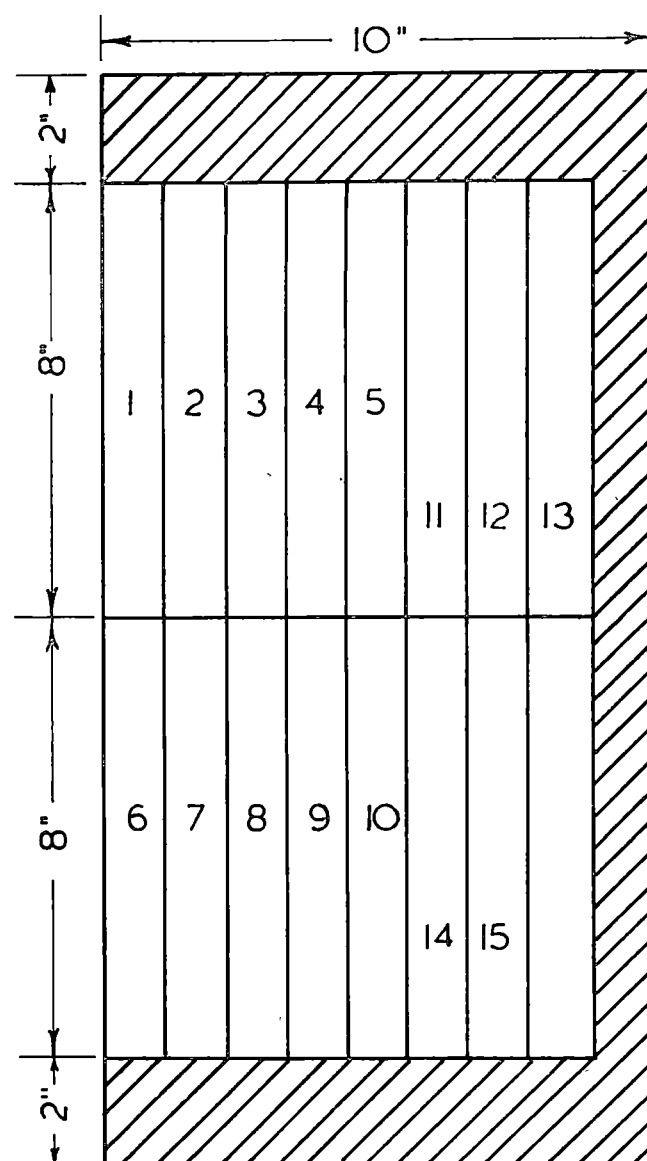


Fig. 30. Preparation of glued joint specimens from 20 in. x 10 in. x $\frac{1}{2}$ in. sheets

Details of the adhesives and setting conditions are given in Table 11.

TABLE 11
DETAILS OF ADHESIVES AND SETTING CONDITIONS

Type of Glue Tested	Setting Conditions		
	Temperature (°C.)	Pressure (lb./sq. in.)	Time Under Pressure
Casein Grasp No. 8	Room temperature	100	16½ hr.
Urea-formaldehyde Beetle Cement H (Hot hardener No. 12)	104	125	15 min.
Phenol-formaldehyde Tego glue film	138-149	125	15 min.

4.2 EXPERIMENTAL PROCEDURE

In order to bring the specimens to equilibrium moisture content before testing, they were conditioned for some time in rooms at appropriate relative humidities. Owing to delay in the manufacture of special wedge grips needed for these tests, the conditioning period extended to about five months, during which time fungus attack reduced the high moisture content casein glued specimens to almost zero strength.

All tests were made at a loading rate of 750 lb./min. in the air-conditioned testing machine. Immediately before testing, the specimens were placed in the machine for an hour at the test temperature and at a relative humidity adjusted to maintain their equilibrium moisture contents.

4.3 RESULTS AND DISCUSSION

4.31 EFFECT OF TEMPERATURE ON SHEAR STRENGTH

At nearly all conditions, moisture content between temperatures was closely controlled. Nevertheless, linear corrections obtained from the results at the test moisture contents were applied to correct the individual shear strengths to 8, 12, and 18 per cent. moisture content at which it was desired to examine the temperature effects.

The corrected mean values of shear strength at the various temperatures and moisture contents are plotted in Fig. 31. The corrected results were analysed for temperature effects.

(a) *Casein*.—On casein bonded joints at 8 per cent. and 12 per cent. moisture content, the temperature

effect was highly significant, strength increasing with temperature. At 8 per cent. moisture content the trend deviated from linearity, at the 5 per cent. level only, strength increasing between 5° and — 15° C. The linear regression coefficients of shear strength on temperature at the two moisture contents were not significantly different, their average value being 1.22 lb./sq. in. per °C.

The temperature effect was about half that reported for the preliminary tests (15 per cent. nominal moisture content), but five times the number of sheets were included in the present investigations in order to reduce the effect of sheet-temperature interaction observed in the earlier experiments.

(b) *Urea-formaldehyde*.—The effect of temperature on the urea-formaldehyde joints varies with moisture content. At 8 per cent. and 12 per cent. moisture content the effect was not significant. At 18 per cent. moisture content, the linear component of the temperature effect was highly significant, strength decreasing on the average by 1.87 lb./sq. in. for one degree centigrade increase. The trend differed significantly from linearity (at the 5 per cent. level), strength decreasing more rapidly as temperature increased above 20° C. The actual experimental means showed that although at 20 per cent. moisture content and 60° C. shear strength was 150 lb./sq. in. (or 18.7 per cent.) less than strength at 20° C. and the same moisture content, it was little less than at 8 per cent. moisture content and normal temperature.

(c) *Phenol-formaldehyde*.—Analysis of the results for the phenol-formaldehyde bonded joints showed the temperature effect to be non-significant at 8 per cent.

moisture content, but highly significant at 12 and 18 per cent. moisture content. The general trend was towards a linear decrease in shear strength with increase in temperature at the higher moisture contents. At 12 per cent. moisture content the non-linear component of the temperature effect was significant at the 5 per cent. level, but in view of the purely linear effects at the other moisture contents

and in the preliminary tests, this deviation from linearity should probably be ignored. The respective regression coefficients of -0.93 and -1.77 lb./sq. in. per $^{\circ}\text{C}$. at 12 and 18 per cent. moisture content agree with the coefficient of -1.09 lb./sq. in. per $^{\circ}\text{C}$. at 13.4 per cent. moisture content established in previous tests. In the extreme case investigated, the mean strength at 60°C . and 20 per cent. moisture content was 12.5 per cent. less than the corresponding value at 20°C .

4.32 WOOD FAILURE

Temperature and moisture content seemed to have little effect on percentage of wood failure determined macroscopically.

4.4 CONCLUSIONS TO PART IV.

From the point of view of the performance of glued joints (wood to wood) in aircraft, the effect of temperature on those bonded with casein, urea-formaldehyde, and phenol-formaldehyde adhesives is not of great importance at low moisture contents.

At 20 per cent. moisture content, a temperature increase from 20°C . to 60°C . may reduce the shear strengths of the urea-formaldehyde and phenol-formaldehyde joints by about 18.7 per cent. and 12.5 per cent. respectively. As temperatures near 80°C . may be encountered in wooden aircraft wings in conjunction with moisture contents as high as 20 per cent. (Greenhill¹⁹), the possibility of greater reduction in shear strength in practice should not be overlooked.

Part V. General Conclusions

Temperature affects the strength properties of wood, plywood, and glued joints in the hygroscopic range of moisture content, in many instances to such a degree that temperature should be considered an important factor in both testing and design.

Basic properties of wood, such as compressive strength parallel to the grain, modulus of elasticity, modulus of rupture, and fibre stress at limit of proportionality, are considerably reduced by increase in temperature; except for modulus of elasticity under some circumstances, the strength-temperature relations are linear. The magnitude of the temperature effect varies systematically with moisture content.

Between species, reduction in these basic strength properties of wood at a given moisture content is

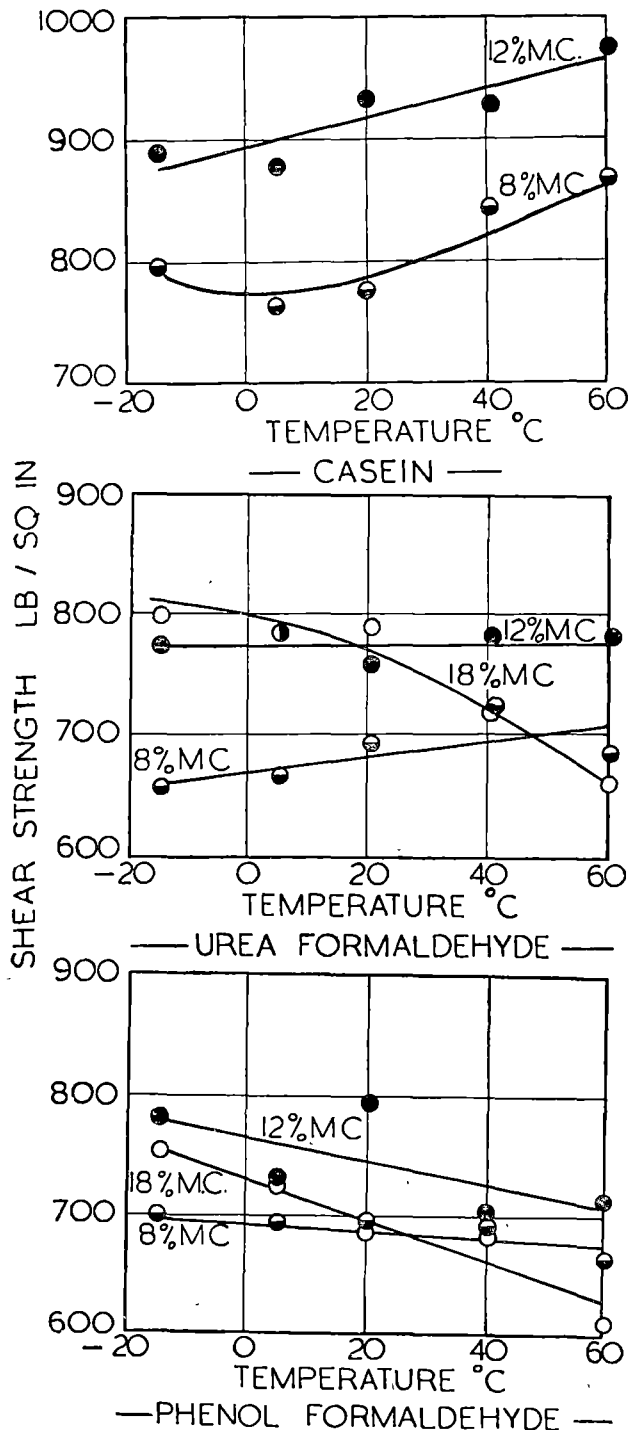


Fig. 31. The effect of temperature on the shear strength of glued joints

reasonably proportional to the value of the corresponding property at 20° C. and the same moisture content. This proportional similarity between the effect of temperature on the various species investigated has made possible the derivation of generalizations from which, at any given moisture content within the scope of these investigations, the effect of temperature on any species may confidently be calculated from knowledge of the strength value at one temperature and the given moisture content. Such general relations have been derived for each of the above-mentioned basic properties. The relation for maximum crushing strength may possibly apply to all usual sizes of test specimens, and that for modulus of elasticity to other specimen sizes and types of test. On the contrary, the relations for modulus of rupture and fibre stress at limit of proportionality in static bending are not independent of specimen size.

The effect of temperature on toughness varies considerably with species, moisture content and temperature range. Increase or decrease in toughness with increasing temperature in some instances is very large; but in the range of temperature and moisture content investigated there appears to be no toughness value much below that existing for the same species at normal temperature and some moisture content in the range. However, for some species, there is a trend at high moisture contents and low temperatures towards a reduction in toughness, which might suggest serious weakening at either higher moisture contents or lower temperatures than those investigated. Variation in toughness with temperature is partly explainable in terms of deflection to failure, which in (static) bending varies considerably between species and moisture contents.

The maximum crushing strength of wet wood tested parallel to the grain is reduced at high temperatures, the effect between species here also being proportional to strength; below freezing point it is more than proportionally increased.

Although the shear strength of solid wood decreases linearly with increasing temperature at the one moisture content investigated, the shear strength of glued joints is not affected to the same extent and may even increase with temperature.

Tensile strength of plywood at 45° to the grain of the outer plies is reduced by both rising temperature and moisture content, the reduction being serious

when both are high. In directions parallel and perpendicular to the grain, the effect of temperature on tensile strength varies considerably with temperature and moisture content; but the only serious reduction below normal strength occurs at very high temperatures and moisture contents, which are attained only in special circumstances; for example in aircraft exposed to solar radiation in hot humid climates.

Modulus of elasticity of plywood in tension is reduced by increase in temperature, except possibly at zero moisture content where the only effect appears to be a slight reduction parallel to the grain. For the parallel and perpendicular directions between 8 and 20 per cent. moisture content, the temperature effect as a percentage of strength at 20° C. is similar for solid wood of the same species in static bending. For the 45° direction, the effect is proportionately greater.

Maximum crushing strength of plywood parallel to the grain is reduced linearly with increase in temperature. On a proportional basis the effect compared with that for solid wood of the same species is identical at zero moisture content and only little less at higher moisture contents. For the perpendicular and 45° directions there is a somewhat similar effect above about 16 per cent. moisture content, but below this the effect appears to be curvilinear. At zero moisture content there is no effect at 45° to the grain direction.

As a result of these investigations, a standard temperature has been adopted in mechanical testing. Greater accuracy in testing and less scattering of results should follow. Uncertainty in results arising from neglect of temperature effects will be appreciated when it is realized that for a seasonal change in temperature from 15 to 40° C. similar tests may yield results differing by some 25 per cent.

Design uncertainty may be even more marked, as under certain conditions of exposure to solar radiation, temperatures well above ambient may be encountered. There is a natural tendency for wood to dry at high temperature, thus compensating for any weakening effect due to temperature rise; but there will be instances, among them, that of the aircraft wing, for which high temperature and high moisture content may co-exist. In this connection, reference is again made to Greenhill¹⁹ who found that an exposed wooden aircraft wing in a tropical location may

reach at least 20 per cent. moisture content simultaneously with temperatures of 80° C. in its upper portion and 50° C. in its lower.

The magnitude of the temperature effects was confirmed in a general manner by experiments conducted at the Division of Aeronautics (Bailey and Richards²⁰). In tests on a number of "Oxford" type aircraft tailplanes loaded to failure at normal temperature, and on others after irradiation sufficient to bring the top-skin to approximately 82° C., the loss of strength at the higher temperature was about 50 and 42 per cent. respectively at nominal moisture contents of 15 and 20 per cent. Heating also reduced the initial slope of the load-deflection curves from 973 to 793 lb./in. and from 1,000 to 880 lb./in. at the respective moisture contents.

The present investigations could, with advantage, be extended to other species, properties and specimen sizes, and to other types of plywood and glued joints. At the same time, the quantitative information derived is sufficiently extensive to indicate the general nature and magnitude of temperature effects to be expected and, in a number of instances, to permit satisfactory estimation of these effects over a wide range of moisture content and temperature.

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